D.T3.1.3
ALTERNATIVE FUEL VEHICLE CONCEPTS AND OPERATIONS ON ROAD AND RAIL

Alternative fuel vehicle Concepts – Report

Index

Abbreviations

Abbreviation	Meaning
BEV	Battery electric vehicle
CT	Combined transport
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
Li-ion	Lithium-ion

1. Introduction

As defined in the project description of InterGreen-Nodes, Deliverable D.T3.1.3 includes a market analysis on the expectation of ports towards green fuel vehicles. Based on this first analysis, concepts for alternative fuel vehicles (rail and road) use in terminal shunting services and operations are being derived. The deliverable focusses on battery electric vehicle and hydrogen fuel cell vehicles, as these drivetrain types promise very high potentials for CO_2 savings, while at the same time are the most challenging, as performance data needs to be translated into technical requirements, for which only little experience exists.

Based on models, partly developed by the research group transport logistics of the Technical University Wildau (PP1), the technical requirements were calculated, using the requirements formulated by the ports. The calculations included the energy requirements, dimensions of energy sources, and performance definition for the drivetrains (based on the operational programme).

2. Introduction to terminal operations

As the interface between the individual modes of transport, intermodal terminals are considered to be the heart of CT. The respective freight is handled in terminals of ports and freight villages. If a terminal is connected to three modes of transport, it is defined as trimodal terminal (p. 3). Likewise, a node of two modes is referred as bimodal. Three types of services are offered in terminals: handling, storage and additional services.

A typical example of additional services is the repair of lifting equipment or containers. Some intermodal transhipment centres also offer so-called trucking as a service, where the terminal operator transports the loading unit of customers over the main and final leg with its own trucks. The specific scope of services of each transhipment node is dependent on many factors such available space as well as transport connections or customer needs. The general operation areas of a trimodal terminal as well as the flow of transports can be seen in Figure 1.

It is based on a container transport, which takes place within road, rail, inland waterway and maritime traffic networks. In container terminals, there are three main areas, which are sea side, yard side and land side. The respective areas are linked by horizontal transports. For each sector, various operations are executed. Additionally, many processes in the terminal are supported by technical equipment.

There are also other types of terminals, which are named according to the goods that are handled. Examples are roll-on/roll-off or bulk cargo terminals. They deviate in certain aspects from container transport, such as transhipment technique and handling equipment. Nevertheless the basic structure is identical, which is why they will not be examined in detail in the further course.
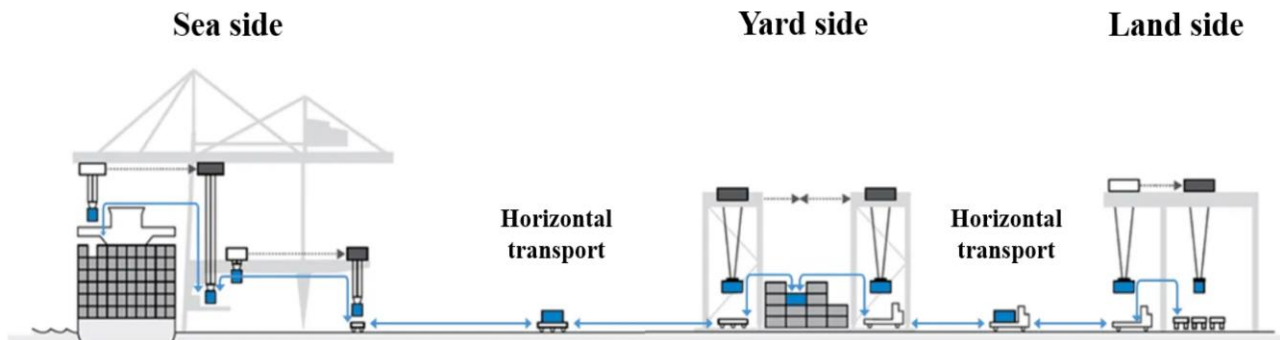
Figure 1: Container terminal system (own figure)

Sea Side

When arriving at the port, cargo vessels wait to moor at the quay. This platform represents the interface between terminal and ship. Alongside the quay, several berths can be found, to which the vessels are assigned. The ships are then moored. Next, the loading and unloading operations by quay cranes begin. The containers that are loaded on vessels are called export containers. They were previously delivered to the terminal from consignors. Import containers are unloaded from the vessels and need to be delivered to their respective recipients. After unloading, the containers are transferred from the quay to the yard side. They are moved by horizontal transport equipment such as reach stackers and terminal tractors. Depending on the layout of the terminal, the loading units can also be transhipped directly onto external trucks or trains from the quayside cranes.

Yard Side

As the centre area of a terminal, the yard side interacts with seaside and landside operations. A yard typically accounts for up to 70 % of the total terminal area. It represents an intermediate storage facility, in which containers remain from a couple of hours up to several weeks. Due to the fact, that storage space is limited, multiple containers are stacked by container handlers.

The yard side enables a temporal decoupling of the transport links. For instance, export containers can be delivered before the arrival of the dedicated vessel and import containers can be picked up for further transport when the delivering boat already left the terminal. Some terminals also operate a depot of empty containers, which are stored at assigned areas. They are also stacked temporarily until they are used again. It is not always possible to reload containers for onward transport immediately after unloading. Sometimes transporting an empty container to its new loading location costs more than the container itself is worth, which is why they are only sent on in bundles.

Land Side

The land side is the interface to the land transport modes. External trucks have to pass gate houses, where containers and transport documents are checked. The layout of the landside area is determined by the connected transport modes. If the operations of external trucks are predominant, this functional area can also be integrated in the yard area. The trucks are then loaded at assigned spaces at the end or in the middle of the stacking yard. In order to serve trains, railway tracks lead into the terminal. Containers are brought by horizontal transport equipment, such as terminal tractors, to cranes ,which take over the vertical handling. For this purpose, mobile reach stackers are also used. Unloading and loading takes place outside the stacking area in order to avoid crossing of rail tracks by yard vehicles. In this way, the safety of the terminal is increased among others. In addition to loading tracks, terminals also have side-tracks, which enable shunting operations of wagons. A diesel locomotive is usually used for this purpose. In some cases road-rail vehicles are deployed for shunting operations as well. As the name suggests, this is a dual mode vehicle, that can travel on both rail tracks and road.

Other layouts include sites which are located in or near the terminal premises. They include offices for staff, that is responsible for administrative activities. Furthermore, the terminal operator provides office accommodation for other entities such as customs, security or mooring companies. Moreover, maintenance workshops for repairing terminal equipment could be found in terminals as well.

3. Zero-emission vehicles

3.1. Definition

The drive concepts investigated will be narrowed down and consequently only so-called zero-emission vehicles will be considered. These are defined as vehicles that do not emit any pollutants during operation and standstill.

The term is based on an environmental legislation passed by the California Air Resources Board, which has boosted the development of environmentally friendly vehicles since the 1990s. There are various drive concepts, but only two configurations can be assigned to the zero-emission class, as these do not emit harmful tailpipe emissions.

Firstly, there are battery-powered vehicles. Secondly, there are FCEV that only emit water vapor, which is not a pollutant. Alternative concepts, that use natural gas or synthetic fuels, can also lead to a significant reduction of emitted air pollutants. However, since they do not completely fulfil the zero-emission condition, they are not considered further. Last but not least, it should be mentioned, that battery-powered as well as hydrogen-powered vehicles are not free of pollutant emissions when considering the complete life cycle. For example, emissions along the production process for the energy sources have to be taken into account

3.2. Battery electric vehicles (BEV)

The development of battery-powered automobiles has a long history. The technology is even older than the invention of petrol-powered vehicles with internal combustion engines (ICEV). The first battery-powered vehicle was built in 1834, more than 50 years before the introduction of the ICEV.

However, further development of electrically powered vehicles was dampened by the fact that they could not compete economically with gasoline and diesel technology. As a result, electric vehicles largely disappeared from the market until the 1930s, and their further development was not encouraged until the oil crisis in the 1970s. Before the turn of the millennium, this was reinforced by an increased demand for greater environmental protection. Over the years, the technology and its technical components have been further optimized in terms of efficiency.

BEV are characterized by a simple system structure. The energy required for driving is stored in a battery that supplies an electric motor and all auxiliary units such as air conditioning or heating. The battery's electric energy is provided by electrochemical processes and converted into a rotational movement by the electric motor. With the help of a differential, the torque is transmitted to the wheels, as in conventional vehicles. Battery-powered drive systems do not always consist of one central motor, but can also be equipped with several individual wheel motors. In addition, electric motors can also be used as generators to feed the vehicle's kinetic energy back into the battery during braking. To ensure proper driving operation, the capacity of the battery must be sufficient for all driving situations as well as allowing an appropriate range. The range is dependent on a lot of factors such as "driving condition and style, vehicle configurations, road conditions, climate, battery type and age".

There are several types of batteries that differ in terms of their technical and economical properties. Lithium-ion (Li-ion) batteries have proven to be suitable energy storage systems. At present time, they are "the leading type of batteries found in electric vehicles due to their high energy density, high efficiencies, and lightweight". Accordingly, an energy density of roughly 200 Wh/kg is achievable, which means that a Li-ion battery with a capacity of 100 kWh weighs at least 500 kg, for instance.

3.3. Fuel cell electric vehicles (FCEV)

Similar to battery drive train concept, the fuel cell is not a new invention. The functional principle of this technology was discovered as early as 1838, after the chemist Christian Friedrich Schönbein recognized, that electrical energy is released when water and oxygen react. In the following year, the physicist Sir William Robert Grove was able to develop the first fuel cell based on this principle (ibid.). Nevertheless, a rapid development was prevented due to the complicated operation at that time. That is why the fuel cell technology could not prevail against the mechanically driven dynamo machine developed at the same time.

Fuel cells were only used for special applications in the further course, as for example in aviation. Nevertheless, the technology of the fuel cell gained more and more importance in the last years in the context of efficient and emission-free transport systems. This is due to enormous development progress in recent years, in which the performance was significantly increased as well as manufacturing costs reduced. Increasing market launches of several hydrogen-powered products prove this as well. The mode of operation of the fuel cell can be understood as a reversed electrolysis. In electrolysis, water is split into hydrogen and oxygen using electrical energy. In a fuel cell, this reaction is reversed and electrical energy is released. Thus, in contrast to the battery, the fuel cell is not an energy storage device, but can be seen as an energy converter. As it generates electric current and no torque, an electric motor is needed for propulsion. The motor is supplied with electric current via power electronics, which then drives the vehicle via a gearbox. In addition to the fuel cell itself, a pressure tank for storing the fuel is required to generate energy. Moreover, a traction battery is installed, with which excess electrical energy as well as converted braking energy can be stored. Apart from that, the battery is also responsible for power bridging or short-term coverage of peak load requirements from the electric motor. FCEV are also referred to as serial hybrids with two energy storage devices (H2 tank and battery) on the one hand, and two energy converters (fuel cell and electric motor) on the other hand. The powertrain design is usually classified into the dominant fuel cell drive and the range extender drive according to the main provision of the drive energy. Figure 2 shows the different configurations.
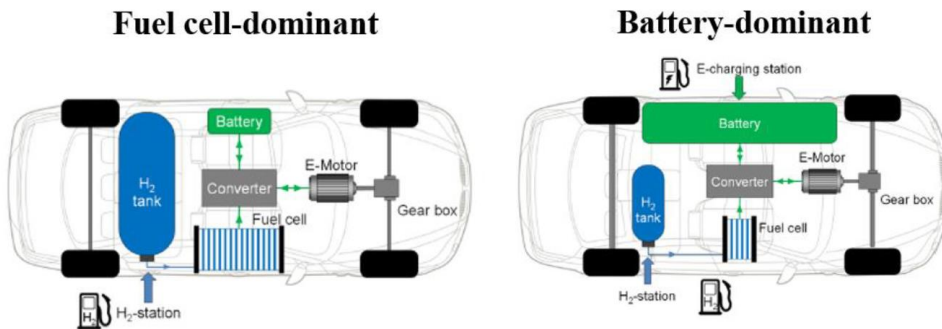
Figure 2:FCEV configurations (own figure)

In the dominant fuel cell system, the driving power requirement is met with the fuel cell, and the battery is used exclusively for the recuperation of braking energy during deceleration and power assistance during acceleration. The fuel cell is therefore very powerful, the battery is usually of high power density and low capacity, and the hydrogen tank is designed as a high-pressure tank, containing several kg of H2 to achieve high ranges. Energy is only supplied by refueling with hydrogen. In the case of the range extender drive, the driving power requirement is covered by the battery, while the fuel cell is used to charge the battery while driving, thus extending the vehicle's range. Range extender vehicles usually have a battery with lower power density and high capacity, a fuel cell with low power and a small-volume hydrogen pressure tank. In the case of range extender drives, the larger battery permits a plug-in vehicle design. This means, that in addition to hydrogen refueling, the vehicle's energy is supplied by charging the battery via the power grid. Mixed forms of the two variants are possible. These are also referred to as the "mid-size fuel cell" concept. There is a large number of different fuel cell types. Stan gives an overview of variants realized so far with their respective characteristics and areas of application. Accordingly, proton exchange membrane fuel cells (PEMF) are particularly suitable for vehicles due to their very high power density at operating temperatures of 20 to 120 ˚C. Furthermore, the fact that it has a flexible operating behavior and the possibility of using oxygen from an air flow also speaks in favor of its use. Rechberger also mentions a fast and cold start capability as well as high efficiency, which is why this fuel cell type is preferred in the automotive industry.

3.4. Comparative analysis between BEV and FCEV

Both drive concepts have individual advantages and disadvantages. In the following, the two concepts will be compared with each other based on selected criteria. In addition to technical issues, infrastructural aspects are also considered. With regard to the efficiency of both drive concepts, battery-powered vehicles have an edge over FCEV (FVEE, 2014, p. 111). Due to the simple system design, an efficiency of up to 80 % can be achieved. With fuel cell technology, efficiencies of 40 to 50 % are possible. Nevertheless, these values are higher than those of the conventional combustion engine, which only achieves an efficiency of 25 %. There are also considerable differences in terms of energy densities. Due to the fact, that the energy density for batteries is lower than for hydrogen, battery-powered vehicles are heavier. Eberle et al. illustrate this in an example showing the relationship between diesel, hydrogen and battery power (2010,

p. 230). For a vehicle with a range of 500 km, a diesel tank system of 43 kg weight and 46 l volume would be required. On hydrogen basis the specifications of the tank system would increase to 125 kg and 260 l. Battery systems are the worst performers: for a range of 500 km, an energy storage system with 830 kg and 670 l would be required. Additionally, Thomas states, that the vehicle mass grows more than linearly if it should achieve a greater range (2010, p. 305). This is because not only more batteries must be added for each additional km, but also the motor or braking system must be reinforced as a consequence of increased vehicle weight. In contrast, FCEVs can achieve longer ranges without greatly increasing vehicle mass. For FCEVs, the range increases with the size of the fuel tank, making them comparable to conventional vehicles in this respect (Belmer et al., 2019, p. 24). Consequently, hydrogen-powered vehicles offer range advantages over BEVs. This also relates to the ability to carry payloads, which is a critical variable for transportation logistics. When designing a BEV, there is often a tradeoff in terms of range as well as achievable payload. To overcome potential operational limitations of BEVs, Teoh et al. summarize several strategies (2018, p. 2). One possibility is to reduce the scope of services. This could be realized by decreasing the number of served customers as well as the size of the served area. Another possible strategy describes the modification of transport operations by optimizing routes and schedules or increasing the fleet size. Furthermore, the use of opportunity charging is mentioned as another measure.

Another benefit of fuel cell technology over BEV is the lower influence of environmental conditions on the operating behavior (Belmer et al., 2019, p. 26). Accordingly, an additional energy consumption of about 10 % can be expected in winter operation compared to average operation. In comparison, batteries are more sensitive to extreme weather conditions. This manifests in a loss of usable capacity and accelerated aging behavior. Charging the battery is another limitation, as the charging time is comparatively high. This may result in limited flexibility during operation. FCEV, on the other hand, have a rapid refueling time. Refueling behavior is similar to that of conventionally powered vehicles (ibid., p. 20). As with gasoline or diesel systems, the refueling process is accomplished through dispensing devices. The aspect of the refueling time and the associated idle time is especially important for economic enterprises, which have only a small time window within their activity patterns. In terms of infrastructural aspects, the use of BEV is in great advantage (Michalk, 2018, p.7). For example, electricity is already produced on a very large scale, so no additional facilities are needed. Additionally, distribution networks already exist in form of electric grids. As a consequence, no further delivery or storage infrastructure is needed. Moreover, area consumption of charging stations is another perk as they are comparably small. For hydrogen storage and distribution specifically assigned spaces are necessary for safety reasons. Additionally, the refueling infrastructure and its related costs for hydrogen-powered vehicles are a prevailing barrier to widespread viability (Moultak et al., 2017, p. 30). Table 1 summarizes the results of the analysis.

Parameter	BEV	FCEV
Efficiency	++	+
Range	-	+
Refueling/Recharging	-	+
Infrastructure	+	-

In summary, no concept is optimal for all applications. The set of decision parameters requires a very detailed examination of the vehicle requirements. Depending on the prioritization of the characteristics for the corresponding application profile, the drive concept must be selected. BEV are particularly suitable for lighter vehicles with low ranges. FCEV, on the other hand, are the better alternative for larger and heavier vehicles.

4. Preliminary work done in the Interreg BSR project Scandria2Act

The objective of the project Scandria2Act from 2016 to 2019 was the promotion of multimodal as well as sustainable transport actions in the Scandinavian-Adriatic corridor. One aspect was the deployment of green fuels, on which Michalk put the most relevant details in a report. Accordingly, electromobility is particularly "well suited in order to install green solutions in city logistics" (Michalk, 2018, p. 6).

Furthermore, the report contains a step-by-step instruction on how to purchase battery electric vehicles for logistics applications.

The first step is to define the objective to derive success indicators. This includes for instance the definition of the reasons for introducing an electric vehicle. After that, one can estimate the necessary range and annual mileage of the vehicle. It is important to have a clear idea of the tour, on which the electric vehicle will operate. For that, it is helpful to analyze vehicle logbooks to derive potential tours with mileages that could be covered by electric vehicles. In the third step the gross weight of the vehicle as well as the necessary payload needs to be specified. For example, the gross weight of the current vehicle(s) to be replaced can be taken as a starting point which will be applied to the electric vehicle. Another approach is to define the required payload and then search for vehicles that have this capacity and find the corresponding gross weight. In step four the necessary battery capacity based on defined range and gross weight criteria is estimated. The following formula is used for the estimation.

$$\text{Energy demand / Battery capacity [kWh]} =$$
$$(\text{max. Range [km]} \cdot 0.3413 + \text{Vehicle gross mass [t]} \cdot 1.3579 + 28.57) \cdot 1.2$$

The formula was used through a regression analysis with n=10. As you can see in the formula, a 20 % safety-addition on capacity is included and covers conventional auxiliary users such as heating and air conditioning. The fifth step focuses on the estimation of costs. Regarding the purchasing price the following formula is given for a rough calculation, which was also developed through a regression analysis with n=10.

$$\text{Purchasing price [€]} =$$
$$\text{Vehicle gross mass [t]} \cdot 2810 + \text{Battery capacity [kWh]} \cdot 920 + 2262$$

Maintenance costs are estimated to be around 60 to 80 % of the cost of equivalent diesel vehicles. However, it should be noted that this is only a rough estimate, as no comprehensive long-term data is available. For energy costs, consumption can be estimated using the formula below.

$$\text{Consumption (kWh/km)} = \text{Battery capacity [kWh] / max. Range [km]}$$

Again, this is only „very rough estimate and it will vary greatly with load, but also with weather and road conditions"(p.23). Once the consumption is calculated, it can be multiplied with the current price per kWh to obtain the consumption costs. In step six the savings of CO_2 emissions are calculated. For that, the current emissions have to be estimated by determining the average fuel consumption per km of the vehicles that will be replaced. After that one can multiply it with the mileage. This result will then again be multiplied with factor 3.16 for a diesel or 2.88 for a gasoline engine. For the planned electric vehicles the CO_2 emission factor per kWh can be obtained from the energy supplier. Multiplying this value with the total consumption, will give the CO_2 emissions for the vehicle, which can be compared with the previously used vehicle. Again, Michalk states, that it is only a very rough estimate, which could be refined with in-depth analysis of utilization- and tour profiles (ibid.).

Step seven includes the selection of the vehicle on the market that matches the requirements and contacting the vendor. In the report, there is a vehicle catalogue, which lists several options of battery electric vehicles (ibid., p.26ff.). A market research will have to be conducted in case there is no suitable alternative available. In the eighth step, one can clarify open questions with regards to the charging infrastructure as well as maintenance, which are of economic importance. Michalk lists several questions (p.23f.) One possible question is to ask about the necessity of own charging stations or the feasibility to use public stations. Regarding maintenance, one possible question would be if the vendor offers a battery exchange after a certain mileage. The last step covers the selection of a funding program. For that, the report also provides a catalogue of several programs in the Baltic Sea region to facilitate the search (ibid., p. 29f.). In fact, subsidies are still needed to penetrate the logistics market as high purchasing costs are a major challenge.

5. Market study

5.1. Method

As the present study is mainly a retrieval of technical requirements, the means of a written survey was chosen. This appeared to be the most sensible method. For example, the form of expert interviews was considered unsuitable, since interviewees should be given the necessary time to coordinate the answers internally in their departments. A previous questionnaire was also used as a guide, which had already been prepared by the research group before this thesis was carried out. It contains initial questions to specify vehicles that could use a green drive technology. The questionnaire has already been sent to and answered by a participating terminal operator in a first preliminary study (see Attachment A). In the course of this, four different vehicle platforms were identified and specified: a transport van in the 3.5 t class, a terminal tractor, a locomotive and a road-rail vehicle. These platforms were considered in the following investigations. For the technical implementation of the present empirical study, an Excel template was created. For each vehicle platform there are 10 questions for specification. The majority of these are open questions. For individual parameters, there were suggested answers based on drop-down lists to increase the quality of the answers. The four vehicle platforms identified in the preliminary study were integrated into the survey. In addition, the mooring vehicle was added as another platform, as it was identified by the project manager as a possible vehicle. In the questionnaire, the terminal operators were asked to specify the five vehicle platforms in terms of their requirements. In addition, they were given the opportunity to add and characterize other relevant vehicles. With regards to the structure of the questionnaire, the exact application purpose was to be described in detail firstly. The respondents were then asked about the desired maximum range for a duty cycle and were also requested to estimate the maximum acceptable idle time for recharging or refueling the vehicle. Other parameters were the maximum permissible gross weight and the desired payload or alternatively towing capacity. The questionnaire also covered relevant auxiliary units for the respective vehicles. Further questions related to the number of needed vehicles as well as the models currently used for this purpose. In addition to technical aspects, terminal operators also had to estimate the maximum acceptable purchase price for these vehicles. Finally, the respondents had the opportunity to make further comments, which had not yet been covered by the previous questions. The questionnaire was developed in close collaboration with the research group. While the survey was not intended to provide in-depth information for a complete technical design of the vehicles, it is an initial retrieval of basic requirements. This ensures, that the requirements can be easily determined and that the asked terminal operators involved are not overburdened. These user requirements can then be forwarded to manufacturers of special vehicles to drive demonstrator development. The questionnaire was sent to the stakeholders in October 2020 by the project manager of the InterGreen-Nodes project with a request for processing. Including the preliminary study, the user requirements of five project partners were recorded by the end of the year, which are described in the further course.

5.2. Participants

Berlin

One of the players involved is the company BEHALA, which is located in the region of Berlin. With about 120 employees, the company operates one of the largest inland ports in Germany in Berlin (BEHALA, n.d.). A handling and transport volume of about 4 million t is achieved per year. The scope of services include the handling of bulk, general and heavy lift cargo. Moreover, its operations comprise the handling of containers. BEHALA operates its own trains as a rail transport and infrastructure company, with which freight trains can be picked up in Berlin and brought directly to the ports, where the goods are then loaded onto a ship. The company is considered as a development driver of logistically sustainable solutions. In this respect, InterGreen-Nodes is not the first project, in which BEHALA has been actively involved. For many years, "BEHALA has been committed to electric mobility for freight transport, and very successfully deploys a 100 % electric-powered tractor-trailer unit, small vans, cars and railway shunting equipment" (VML-BB, n.d.).

Rostock

With a total area of 750 ha, the Port of Rostock is the largest German port in the Baltic Sea region. It is the fourth largest seaport in Germany after Hamburg, Bremerhaven and Wilhelmshaven (Rostock Port, 2020a, p. 18). In 2019, approximately 25 million t were handled in total. The number of direct and indirect employees of the Rostock port industry is about 16,000 (Rostock Port, 2020b, p. 2). Rostock Port GmbH is responsible for the management, development and maintenance of the respective infrastructure. With its seven different terminals, the seaport has a wide range of services. Upstream of the port is a marshalling yard with about 180 km of track. In addition, there are 54 km of tracks on the port site that enable a direct transshipment without additional storage time of the goods (ibid.).

Koper

The port of Koper is located in the northern part of the Adriatic Sea. It is the only Slovenian multipurpose port. Luka Koper Group, which was founded in 1957, has about 1,600 employees and operates 12 specialized terminals and its port activities are related to cargo and passenger transport (Richter, 2019, p. 2). The core business of the port comprises the transshipment and warehousing of a variety of goods. The port area consists of 280 ha of land. Additionally, there are 35 km of railway tracks within the port area. In 2018 the total throughput amounted to approximately 23 million t (ibid.). As the largest container terminal in the Adriatic as well as third largest car terminal in the Mediterranean region, the port has a significant effect on the national economy (Slobko Jerman, 2016, p. 2)

Bologna

The Interporto Bologna is a freight village and located in the Emilia-Romagna region, which is one of the most heavily industrialized areas in Italy (Haug, 2019). It covers a total area of 410 ha and

features a railway system, that is larger than 65 ha (Interporto Bologna, 2019, p. 2). The logistics hub includes three bimodal terminals. At the freight village, roughly 120 transport and logistics companies are located, which employ more than 4,000 people in total. In 2018, Interporto Bologna handled 1.2 million t of rail freight goods as well as around 12.7 million t of trucked goods (Haug, 2019).

Budapest

The last project partner is the Freeport Budapest. It is a logistics center with an area of 153 ha, in which warehousing, railway and shipping services are offered (BSZL, 2019, p. 3). The freight village operates the only trimodal container terminal in Hungary (ibid., p. 6). In terms of railway operations, Freeport Budapest has a track network with a length of about 16 km. In 2016, almost one million t goods were transshipped in total (Jovanovic, 2017, p. 81).
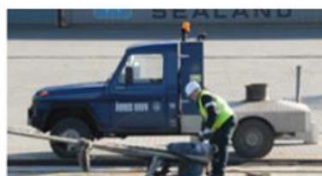
5.3. User requirements for selected vehicle platforms

In the further course of this study, six vehicle platforms named and specified by the interviewed terminal operators are examined in more detail. These include road vehicles such as a transporter with a maximum total weight of 3.5 t, a mooring vehicle, a terminal tractor and a container handler as well as rail-bound vehicle platforms like a road-rail vehicle and a locomotive. Other vehicles were also named in the survey, but these will not be considered further due to various reasons. For instance, a boat was specified, which is not in the scope of the work package as it only considers road and rail vehicles. The identified vehicles along with their required specifications can be viewed in Attachment A and B.

Transport van (3.5 t)   Mooring vehicle   Terminal tractor

Container handler   Road-rail vehicle   Locomotive

Transport van (3.5 t)

For the majority of the interviewed terminal operators, the van would be used for transport of maintenance equipment and supervisory tasks. Additionally, the freight village Bologna mentions the usage for last mile express delivery outside the port area. Depending on the specific application, maximum distances between two charging cycles range from 200 to 1,000 km. Regarding the desired payload, the ports specify a range from 1 to 2 t. Typical auxiliary units like heating, air conditioning and radio were considered desirable. The port of Berlin also mentioned the possibility to charge an external battery, which can be charged by the van. Since there is not any further quantitative data, this point was not considered in the ongoing technical dimensioning. Most of the respondents indicated a duration of at least eight hours for the longest acceptable idle time between two duty cycles. Only the port of Rostock specified a maximum duration of two hours for reloading or refueling. With regard to the maximum purchase price, the two ports Bologna and Koper stated a limit of 50,000 €. For other ports, a zero-emission transporter with a total weight of 3.5 t should cost a maximum of 20 to 50 % more than a conventional fuel driven vehicle. Regarding the currently used vehicles, the port operator Rostock uses the vehicle models Vito and Sprinter from the manufacturer Mercedes-Benz for the purpose of equipment transport. In Budapest Dacia Duster and KIA K2500 are used for maintenance and supervisory tasks. The most important parameters can be found in Table 2. In addition, the original answers of the questionnaire can be viewed again in Attachment A and B.

Parameter	Berlin	Rostock	Bologna	Koper	Budapest
Purpose	Craftsman transport	Equipment transport	Last mile express delivery	Internal logistic & maintenance	Maintenance & surveillance
Max. Range [km]	250	200	600	500-1,000	200
Max. Payload [t]	1,5	2	1,5	2	1
Gross weight [t]	3,5	3,5	3,5	3,5	3,5
Max. Idle time [h]	n.a.	2	8	>8	8
Max. price [€]	n.a.	120 % of a diesel van	50,000	50,000	150 % of a diesel van
Currently used vehicle	n.a.	MB Vito & Sprinter	Citroen, Ford, a.o.	n.a.	Dacia Duster & Kia K2500

Mooring vehicle

The two ports of Rostock and Koper can imagine using mooring vehicles with green propulsion systems. This vehicle type is used to fix vessels at the pier. The interviewee of the German port states a required maximum range of 200 km per duty cycle. According to the Slovenian project participant, the car needs to reach 500 km for its mooring operations. With regards to the towing capacity the vehicle would have to tow a mass of two t. When considering relevant auxiliary units in addition to heating and air condition systems, the Slovenian port indicated, that there must be enough battery power to operate a spill winch used for mooring. Furthermore, the terminal operator in Rostock states two hours as longest acceptable time frame for recharging or refueling. For the operations in Koper it would be sufficient to keep the idle time of this vehicle type at more than eight hours. Regarding the purchase price, the expectations are the same as for the transport van with a gross weight of 3.5 t: Rostock would accept a 20 % higher price compared to a conventionally powered vehicle and Koper fixes a maximum value of 50,000 €. The number of vehicles required per port is in the single digits area. The German port uses one mooring vehicle and the Slovenian five. The currently used models are the Unimog from Mercedes-Benz and the Hilux from Toyota. These versions will be discussed in more detail on the following pages. The answers of both ports are summarized in the following Table:

Parameter	Rostock	Koper
Purpose	Support port crew to moor vessels	Mooring operations
Max. Range [km]	200	500
Max. payload [t]	n.a.	2
Gross weight [t]	n.a.	n.a.
Max. Idle time [h]	2	>8
Max. Price [€]	120 % of a diesel model	50,000
Currently used vehicle	MB Unimog	Toyota Hilux

Terminal tractor

The terminal tractor was specified by Berlin, Bologna, Koper and Budapest. According to the Italian freight village, this vehicle platform will be used for shunting operations with semitrailers between warehouses or parking areas. Most of them are used in container terminals, but they are also integrated in the transport operations of timber and general cargo terminals. The port of Berlin also considers the use of yard tractors on public roads outside the port area. Depending on the intended application, the transshipment centers have specified desired maximum ranges from 40 to 400 km. In terms of the required payload, the terminal tractors should be able to carry at least 20 t. Furthermore, the freight village Bologna requests, that the vehicle needs to be capable to move at least one complete semi-trailer with an average weight of 35 t. With 60 t, Koper indicates the heaviest payload to be carried within the port. Regarding the gross weight of the tractor without trailer, the Hungarian project participant states it as about 10 t. The idle time for this vehicle type ranges from four to more than eight hours in order to refuel or recharge. Conventional vehicle models that are used by the participating ports are produced by the manufacturers such as TICO, Kalmar, Terberg and Mafi. In case these vehicles should be replaced by zero-emission yard tractors, the maximum purchasing costs are 100,000 € (Bologna) and 200,000 € (Koper). The port of Budapest stated, that a new electric terminal tractor costs around 250,000 € net, which would be too expensive. In general, it sees no need for replacing its current diesel tractors since accordingly they are still in perfect condition after 15 years of operation. In the following table you can find the answers from the project partners.

Parameter	Berlin	Bologna	Koper	Budapest
Purpose	Container transport within port and on public roads	Shunting of semi trailers between warehouses or in parking areas	Shunting in container, timber & general cargo terminal	Shunting inside container terminal
Max. Range [km]	40 (if only inside port) / 60	400	400	100
Max. Payload [t]	40-44	35	60	25
Gross weight [t]	n.a.	n.a.	n.a.	10 t
Max. Idle time [h]	n.a.	4	>8	8
Max. Price [€]	n.a.	100,000	200,000	<250,000
Currently used vehicle	n.a.	TICO, Kalmar, Terberg, Mafi, CVS	Trelebog, Mafi	Kalmar

Container handler

The container handler was specified by Budapest (see Table 5). The task of this vehicle platform is to maneuver and stack containers. In order to be able to replace the currently operating diesel models of this vehicle type, Budapest specifies a maximum range of 100 km between charges. Two different variants of the container handlers are required, varying in terms of their transported payload. Firstly, a capacity of 11 t is required to ensure the transport of empty containers. Secondly, the port would need a heavier version with a lifting capacity of 45 t. With regard to the maximum gross weight, a value of 70 t was estimated, which will be validated in the market analysis part. Empirical study 33

Budapest states, that it is still acceptable to have an idle time of eight hours for this type of vehicle. Regarding the auxiliary units, apart from heating and air condition systems, no other units were specified by the port and it did not defined a maximum purchase price. Currently, 10 cargo handlers are in operation in Budapest: six with a capacity of 45 t and four with a capacity of 11 t. Both versions are from the special vehicle manufacturer named Kalmar.

Parameter	Budapest
Purpose	Handling of (empty) containers
Max. Range [km]	100
Max. payload [t]	11 (empty containers) & 45 (loaded containers)
Gross weight [t]	70
Max. Idle time [h]	8
Max. Price [€]	n.a.
Currently used vehicle	Kalmar 11 t & Kalmar 45 t

Locomotive

The locomotive was specified by four ports. It is used for shunting and line operations of trains and wagons. For these purposes, it can either be used inside or outside the port. According to the requirements of the Berlin port operator, the locomotive must be able to run 100 km with full load without any interruptions. The other ports did not specify a distance, but did so for operating hours. Here the running times between two charges differ. While Budapest indicates a running time of 10 hours per day, it is 70 h for the Italian transshipment point from Bologna. The longest desired running time is 500 operating hours for Koper, which seems to be a typo. According to three of the ports, the locomotive must be able to pull a load of at least 2,000 t. Berlin additionally states, that a propulsion power of 1,700 kW is required for this. Budapest demands an even higher towing capacity. The gross weight of the locomotive is estimated at around 60 to 80 t in order to pull the respective masses. Additionally, the longest acceptable idle time is at most eight hours for two ports and only Koper permits a longer idle period. The involved interviewees also stated, that they needed two to three locomotives for their purposes. With regard to the purchase price, two ports indicated a maximum permissible limit of 1.7 million and 2.2 million € each. Currently, mainly models from the rail vehicle manufacturers CZ Loko and Vossloh are used. The table summarizes the most relevant parameters.

Parameter	Berlin	Bologna	Koper	Budapest
Purpose	Shunting/ Line Locomotive	Train and wagon shunting	Deliver/Dispatch train sets inside whole port	Shunting operations
Max. Range [km]	100	70 working hours	500 working hours	10 working hours / day
Max. towing capacity [t]	2,000	>2,000	2,000	>2,000
Gross weight [t]	n.a.	n.a.	64-84	72
Max. Idle time [h]	n.a.	8	>8	8
Max. Price [€]	n.a.	1.7 million	2.2 million	n.a.
Currently used vehicle	n.a.	CZ Loko	CZ Loko, Vossloh	MÁV Class M44 & 74 SK

Road-rail vehicle

The project partners Berlin, Bologna and Koper see the potential for using green road-rail vehicles. According to them, this vehicle platform is used for light shunting operations of trains and wagons. In the context of short movements, only short ranges are achieved during a duty cycle. Berlin estimates these at 10 km for example. Bologna specifies a working duration of 50 hours. The road-rail vehicle must be designed in such a way, that a mass of about 1,000 to 1,500 t can be towed. Koper is the only respondent to state, that the gross vehicle weight must be in the range of 25 to 35 t to be capable of towing these volumes.

With regard to the idle time, respondents agree, that a maximum of eight hours would be acceptable. In contrast, there are high deviations in the required purchase price. Bologna considers the road-rail vehicle as too expensive with a price above 120,000 €, while Koper has a tolerance limit of 650,000 €. Moreover, the required number of this vehicle type ranges from one to seven according to the interviewees. Currently used models are for instance the converted Unimog from Mercedes-Benz as well as different versions of Zwiehoff and Zephir.

Parameter	Berlin	Bologna	Koper
Purpose	Light shunting	Train and wagon shunting	Movement of train sets in terminals
Max. Range [km]	10	50 working hours	Only short movements
Max. Towing capacity [t]	1,000	1,500	1,000
Gross weight [t]	n.a.	n.a.	25t-35t
Max. Idle time [h]	n.a.	8	>8
Max. Price [€]	n.a.	120,000	650,000
Currently used vehicle	n.a.	MB Unimog, Zephir	Zwiehoff, Zephir

6. Implications from the empirical study

6.1. Derivation of technical properties

In order to estimate the energy demand for the individual vehicle platforms, the formula developed for the Scandria2Act project was used. However, during the project, it became clear, that the formula was subject to some restrictions. For example, the energy demand could only be determined for light road vehicles. As a result of this, the formula was only used for the transport van, the mooring vehicle and the terminal tractor. For the other vehicles, an alternative methodology was worked out case by case, which will be described in more detail in the respective subsections. Two additional parameters were derived from the estimated energy demand. The first is the battery weight. This parameter can be determined by dividing the battery capacity by the specific energy density. In this thesis, an energy density of 200 Wh/kg will be used for the calculations, as it is the upper limit for Li-ion batteries, which are most commonly used in BEV. The second parameter is the charging capacity. It describes the infrastructural requirements to enable battery recharging within a certain period of time. Its calculation is based on the maximum acceptable charging time specified by the surveyed project partners. The charging capacity can be roughly estimated by dividing the battery capacity by the charging time. In addition, a 15-minute safety buffer was added to the times from the survey.

Transport van (3.5 t)

For the transport van with a total weight of 3.5 t, the desired distance of 200 km results in a battery capacity of 122 kWh. With an additional 50 km, the battery capacity increases by a further 20 kWh to 142 kWh. With a range increase from 200 to 500 km, the required energy doubles to 245 kWh. For the 600 km range indicated by the port of Bologna, the battery capacity would be 286 kWh. For a distance of 1,000 km in combination with a gross vehicle mass of 3.5 t, 450 kWh would be needed according to the formula.

With regard to compliance with the charging times, the following conclusions can be drawn. The maximum charging capacity is 70 kW as required by the port of Rostock, which defined two hours as acceptable charging time for 122 kWh. In the case of Budapest, where even eight hours would be feasible for charging the same battery capacity, a charging capacity of 16 kW would be sufficient. In the case of Koper, the 450 kWh battery requires a charging capacity of at least 58 kW to fulfil the time requirement of eight hours. Thus, for each case, the vehicles be charged with already developed charging stations. Regarding the payload for conventionally powered vehicles, it can generally be said, that it is limited to about 1.5 t for versions with a total weight of 3.5 t. For instance, the payload of the diesel-powered version of the Mercedes-Benz Sprinter vehicle used by the port of Rostock is about 1.5 t. For the other mentioned vehicle models like Mercedes-Benz Vito and KIA K2500, the transport weight is limited to one t. Some ports specified a desired payload of two t for the green propulsion solution, which is not feasible for this vehicle platform. When considering the battery weight, it becomes clear, that for most of the applications the range and payload requirements are not feasible. For Budapest with 600 km range, the batteries would weigh about 1.4 t. For 450 kWh, even more than 2.2 t would be needed, making a battery/gross

weight ratio of 64 %. It should be emphasized once again, that the energy density of 200 Wh/kg is roughly the upper limit of Li-ion batteries. Using a more conservative energy density would increase the mass of the battery and consequently reduce the payload.

Mooring vehicle

Mooring vehicles are modified flatbed trucks. At first, the weight class for this application is determined. According to the survey, the vehicle models used are the Hilux from Toyota and the Unimog from Mercedes-Benz. The Hilux has a maximum gross weight of approximately 3.2 t (Toyota, 2018, p.10). It is also assumed, that a maximum gross weight of 3.5 t is sufficient for the Unimog in this application. Therefore, the previously estimated energy demands for the transport van can be transferred to the mooring vehicle. The required ranges are 200 and 500 km. At 200 km the demand is 122 kWh and at 500 km it is 245 kWh. The main task of this vehicle platform is to transport the mooring personal to the vessels as well as to haul in ship's lines with an electric winch machine. In comparison to the transporter, it is therefore considered likely, that the payload requirements are lower and there is accordingly more space for a larger battery. In addition to the consideration of the horizontal movement, the energy required for the electric winch machine must also be taken into account. The mooring company Festma, which is operating at the port of Bremerhaven, serves as a reference. Their winches have a maximum traction force of 1.5 t (Arndt, 2019). The motor power of an electric winch machine with this load requirement is approximately three kW. Assuming that the winch is activated for 10 min on each ship to be moored, an energy demand of 0.5 kWh per boat can be assumed. Based on the underlying results, the use of a battery-powered variant is a realistic scenario for this vehicle platform assuming a range of 200 km as specified by the port of Rostock.

Terminal tractor

Based on research about the kerb weights of conventionally operated terminal tractors as well as the electric version from the KV-E-Chain project, a vehicle weight of 10 t is estimated for battery dimensioning. In addition to the kerb weight, all the payloads indicated by the interview partners were taken into account. Thus, five different total masses are shown for each range. This diversity of variants is intended to cover as many applications as possible.

The individual consideration of the empty weight results in required energies of 67 to 214 kWh for the respective trips. For transports of the maximum payload, which was specified by the port of Koper as 60 t, 165 kWh would be needed for a distance of 40 km and up to 312 kWh for the maximum distance of 400 km. Since empty runs and runs with transported goods occur alternately in practice, the battery capacities can also be estimated proportionately on the basis of the diagram. Assuming a range of 40 km and a 50 % split between empty runs (67 kWh) and transports with a total weight of 70 t (165 kWh), the average value of 116 kWh would be sufficient. In terms of the necessary charging capacities, the following conclusions can be drawn. The Budapest case results in 100 km and 132 kWh battery capacity. According to the survey, the available charging time is eight hours. A charging capacity of 17 kW would be sufficient to charge the vehicle according to these requirements. For the use cases Bologna and Koper, a higher charging capacity is required. 400 km and 45 t total weight result in a battery capacity of 271 kWh for Bologna. Since

the maximum charging time was given as four hours, the required charging capacity would be approximately 72 kW. For Koper with a maximum of 312 kWh and more than eight hours acceptable time frame for charging, 40 kW would be needed. The calculations of battery weight yield masses up to 1,560 kg for 312 kWh with a specific energy density of 200 Wh/kg. The electric yard tractor from the KV-E-Chain had only a battery energy density of 91 Wh/kg (Jung, 2016, p. 3). This would increase the battery weight to 3,428 kg. It can be assumed, that empty weights of 10 t would not be feasible for very high battery capacities, which results in further reduction of payload mass.

Container handler

For the container handler, the methodology for estimating energy demand changes. There are two reasons for this. Firstly, the formula used previously can only be applied to light vehicles. Secondly, in addition to the horizontal movement, a vertical component that results from the lifting of containers must also be taken into account. The following formulas are applied to estimate the energy demand:

$$\text{Horizontal movement: } E_{Kin} = \frac{1}{2} \, m_{Vehicle} \cdot v^2$$

$$\text{Vertical movement: } W_{Lift} = m_{Container} \cdot g \cdot h$$

For the horizontal energy demand, the formula of kinetic energy is used. It consists of two factors: gross weight and the velocity of the vehicle. For the vertical energy demand, the formula of the lifting work is applied. It consists of three factors: the mass of the container to be lifted, the gravitational acceleration, fixed to 9.81 m/s², and the height, by which the container is lifted. To estimate the horizontal energy demand, the service weights of the two container handler variants must be determined first. According to the survey, the empty container handler should have a lifting capacity of 11 t. This requirement is met by the DCG110-45ES manufactured by Kalmar, for example. Depending on the stacking height, it has a service weight of up to 45 t (Kalmar, 2018a, p. 11). In the case of the loaded container handler, a lifting capacity of 45 t was specified by Budapest in the survey. Additionally, it was stated, that the currently used diesel vehicles are manufactured by Kalmar. However, no masted container handler with a lifting capacity of above 41 t could be found (Kalmar, 2018b, p.6). Other manufacturers, such as Hyster, also specify their loaded container handlers with a maximum lifting capacity of only 40 t (Hyster, 2018, p.4ff.). Higher capacities can only be achieved by using reach stackers. An example is the variant RS46-41XD/62S from Hyster, which can stack five 9'6" containers weighing up to 46 t each (Hyster, 2020, p. 6). The service weight for this model is 87.5 t. Two load cases are considered for each vehicle configuration. Firstly, the payloads specified in the survey are taken into account, which are 11 t for the empty container handler and 45 t for the loaded container handler. In addition, a payload of four t is assumed for the empty container stacker in the second load case, which roughly corresponds to the empty weight of a 40-foot-long high cube container (Hapag-Lloyd, 2016, p. 13). When loaded, the maximum gross weight of this container is 32.5 t, which is the second load case of the full container handler (ibid.). The energy demand is to be estimated with the help of a fictive reference profile. It is a fivefold stack of high cube 9'6" containers, which are just under three m high. A handling time of 30 seconds was defined for loading and unloading the containers.

Between handling, the vehicle travels 100 m each time to pick up containers or to move them to their destination. The vehicle accelerates to 20 km/h.

The whole procedure takes a total of eight minutes. During this time, a distance of one km is covered. The respective energy demands were calculated for the individual steps of the process. The required energy was then extrapolated linearly to 10 operating hours. A total distance of about 75 km is covered in this sample application. Several simplifications are also made for the calculation. For example, the containers are each picked up from the ground. In addition, the vehicles move uniformly. Likewise, it is assumed, that lifting to the target height already takes place before transport. Additionally, the container mass is constant in this example.

In the following, the calculated energy requirements for the individual vehicle configurations are presented over the duration of 10 h
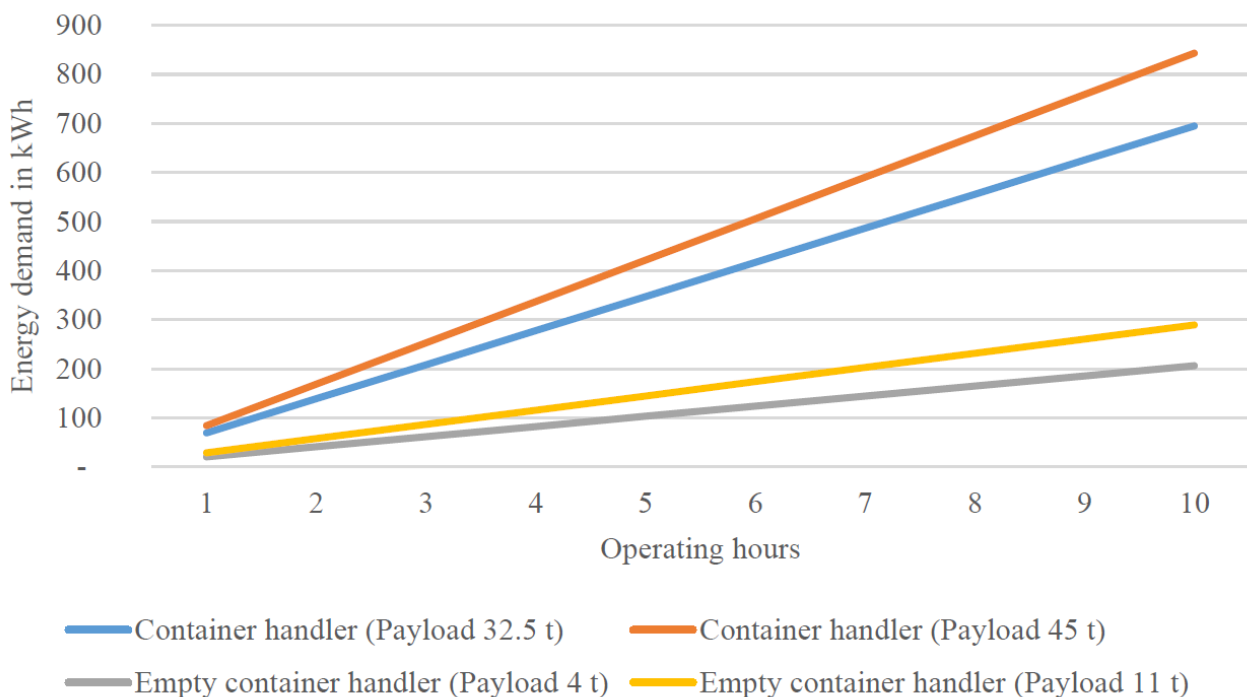
With an additional safety margin of 10 %, the required battery capacity for the loaded container handler is 695 to 843 kWh depending on the load case. With an energy density of 200 Wh/kg, this would result in a battery weight of 3.5 to 4.2 t. In addition to this, the necessary charging power is also calculated to meet the requirements from the survey. For Budapest, 90 or 109 kW would be required with the estimated battery capacity in order to fully recharge the vehicle within eight hours. For the variant of empty container handlers, the needed energy demand is between 206 and 289 kWh for the two payloads considered. Battery weights of 1 and 1.5 t for 200 Wh/kg are to be expected here. Based on the estimated battery capacities, the charging infrastructure would have to be designed in the range of 27 to 37 kW if this vehicle type needs to be recharged within eight hours.

Shunting locomotive

For this rail-bound vehicle platform, an alternative procedure for estimating the energy demand was selected again. It is important to say, that from now on only shunting operations will be considered, as no data for line service was available. Four different load profiles for locomotives in shunting operation could be found in the literature. Of these, three are statistical distributions, which are shown in the following table. In this table, the corresponding power ranges of a locomotive are shown pro rata temporis.

Load profile 1 - EUROMOT								
Nominal power (%)	0	30	50	60	75	90	100	
Time share (%)	65	20	10	4,50	0	0	0,50	
Load profile 2 - Siemens								
Nominal power (%)	0	0-5	5-10	10-15	15-30	30-50	>50	
Time share (%)	33	41	8	6	6	3	3	
Load profile 3 - EPA								
Nominal power (%)	0	12,5	25	37,5	50	62,5	75	87,5	100
Time share (%)	60	12,5	12,5	5,0	3,0	3,0	2,5	0,5	1,0

The first load profile is provided by EUROMOT, which is the European Association of Internal Combustion Engine Manufacturers (Knörr et al., 2003, p. 62). According to them, at most 50 % of the nominal power of a shunting locomotive accounts for 95 % of the operating time. 65 % of the time is assigned to idling. The maximum nominal power of a locomotive is required for 0.5 % of the operating time. The second load profile was provided by Siemens and describes the shunting operation in the rail yard of a German steel company (ibid.). In this case, the ranges of power were not clearly defined. For example, it was stated, that three % of the operating time over 50 % of the rated power is utilized. For further calculation, the average value was used in each case. This means, that the motor is used at 75 % of its nominal power in three % of the operating time. This could lead to deviations, which should be taken into account. The third load profile is a statistical distribution from the US-American Environmental Protection Agency (EPA) (Kache, 2014, p.33). On a reference basis of 333 h, the shunting locomotive is idling 60 % of the time. To determine the energy demand based on the three load profiles, the calculations use a nominal power of 1,700 kW, which was specified by Berlin in the survey. The fourth and last load profile describes a duty cycle for an in-service yard switching locomotive operating in the US-American port of Long Beach (Miller et al., 2007, p. 4). In this example peak power reaches 600 to 1,100 kW for durations of a few minutes only. Idle time accounts for 50 to 90 % of the overall

operation schedule. For the fourth load profile, the energy demand can be derived from a diagram, which is illustrated in the respective paper (ibid.). The respective energy requirements of the four use cases are shown in Figure 13 over a time span of 10 operating hours.
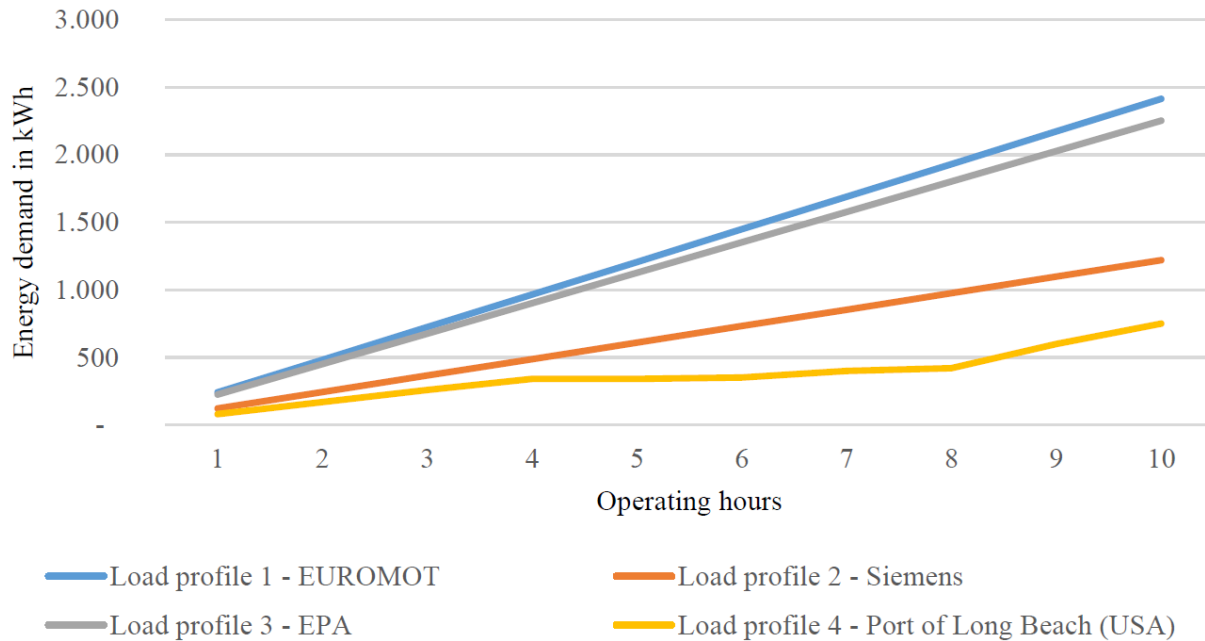
Regarding the needed energy, the load profiles differ greatly from each other. The demand of the fourth load profile is the smallest with 750 kWh. This is partly due to the fact, that the locomotive in this example reaches a peak power of 1,200 kW, whereas the other profiles were calculated with 1,700 kW. Based on the second load profile by Siemens an energy demand of 1,220 kWh was derived. Almost twice as much energy is required for the third load profile with 2,253 kWh. The load profile from EUROMOT requires the most energy with 2,414 kWh. The battery capacities may set high demands on the charging infrastructure. The ports stated in the survey, that about eight hours are available to charge the battery. Assuming the load profile with the highest energy demand, the charging station would need a power of at least 311 kW. Due to the long idle times, intermediate charging seems to be recommendable. However, the feasibility of this procedure must be examined in more detail. The battery weights for the individual load profiles also differ greatly. With a capacity of 750 kWh, the weight of the energy storage system is about 3.75 t. If the battery has a capacity of 2,414 kWh, the battery would weigh approximately 12 t.

Road-rail vehicle

The road-rail vehicle is another special use case, for which the previously used methods cannot be used. In order to assess the energy demand for this vehicle platform, the port of Westhafen in Berlin was visited. There, the operations of such a vehicle could be observed in a real application scenario, which is described in more detail below. The port operator uses the road-rail vehicle to shunt bulk freight wagons within the terminal. A locomotive previously moved the wagons to a port pier with two tracks. Next to the tracks, there is a bulk storage area on the land side and a dock for boats on the sea side. The road-rail vehicle is used to move the wagons to the conveyor belts that transship goods as shown in Figure 14. All in all, the distance covered is very small and only maximum speeds of five km/h are reached.

Until 2014, a diesel-powered Unimog was used. Since then, a battery-powered model of the company Windhoff has been available (see Figure 15). In this use case, the battery capacity is 124 kWh. According to the local operations manager, a maximum of 10 assembled wagons are shunted with the electric vehicle. On the day of the observation, there were 10 wagons at approximately 50 t on each of the two tracks. It can therefore be assumed, that the road-rail vehicle accelerates 20 times in order to move the coupled wagons with a total mass of up to 500 t. The presented shunting and transshipment procedure is carried out in two shifts. According to the operations manager, the battery capacity is sufficient to operate without intermediate charging during this period. Although the electric road-rail vehicle is only used on a single day of the week, the operation is profitable from the port's point of view, as it does not consume energy during the idle time when unloading. Likewise, one-man operation is possible, which leads to savings in terms of personnel costs. The worker can stand next to the conveyor belt and move the road-rail vehicle and the wagons by remote control.

6.2. Development status

Transport van (3.5 t)

The range of zero-emission vehicles in this market segment is diverse. Most manufacturers have already developed a green solution. BEVs are available by a wide margin. Table 9 shows a selection of relevant vehicles from different manufacturers.

Vehicle type	BEV	BEV	BEV	BEV	BEV	FCEV
Product name	Iveco Daily Electric	VW E-Crafter	Mercedes eVito	SAIC Maxus EV 80	Renault Master Z.E.	Renault Master Z.E. Hydrogen
Battery capacity (+RE) [kWh]	60	36	41	56	33	33 (+56)
Range [km]	280	175	189	200	200	350
Payload [kg]	700	970	1,015	950	1,128	1,200
Gross weight [kg]	3,280	3,500	3,200	3,500	3,100	3,500

This confirms the previously mentioned aspect, that potential users currently have to make compromises in terms of range or the cargo that has to be carried. There is no BEV model, which simultaneously meets the requirements of the terminals for both required distance and payload. Thus, only one condition can be met. Furthermore, it can be deduced from the specification overview, that about 35 % of the total weight is payload. In contrast, the diesel version of the Mercedes-Benz Sprinter used in the port of Rostock, for example, can transport 1.5 t of cargo at 3.5 t gross weight, which corresponds to a share of 43 %. From a technical point of view, it is obvious, that current BEV are not competitive with conventional variants in this segment.

To reduce the gap to ICE regarding the technical properties, FCEV could play an important role. For example, the manufacturer Renault is launching its vehicle model Master, which is equipped with a fuel cell. It will serve as a range extender and starts working, once the battery reaches 80 % of its charge level (Reichel, 2019). The fuel cell has the ability to recharge the empty battery by itself. Accordingly, two hydrogen tanks with a capacity of 106 l for 2.1 kg of hydrogen at 700 bar are installed. This adds a further 56 kWh to the BEV's battery capacity of 33 kWh. The range is increased by more than 150 km to 350 km compared to the Renault Master in pure BEV configuration. The fact, that the overall weight of the vehicle has been increased by the installation of the fuel cell system, means that there is no loss in terms of payload weight. However, problems with regard to lower volumetric cargo capacity could arise and might have to be considered. More vehicles are under development in this context. Another example is the VW Crafter HyMotion, which was presented at the 2018 International Motor Show (Volkswagen, 2018).

It is a concept van with a 4.2 kg hydrogen tank, which enables a range of 350 km. Due to the modular design of the tanks, larger tanks can be installed, achieving up to 500 km. In contrast to the battery electric E-Crafter, the battery capacity of the vehicle variant with fuel cell shrinks from 36 to 14 kWh (Conrad, 2018). According to VW, the technical concept is close to reach production phase (Volkswagen, 2018). Contrary, Conrad states that the E-Crafter HyMotion will not go into serial production until the availability of hydrogen stations has been increased extensively (2018).

Terminal tractor

Several versions of battery electric terminal tractors are already produced by various manufacturers. For instance, the BYD 8Y is designed for the long range with a storage capacity of 217 kWh (PG&E, n.d., p. 16). Accordingly, this vehicle model is capable of operating more than 10 hours and transport a payload of about 37 t. Furthermore, the Canadian manufacturer Kalmar offers the T2E 4x2 terminal tractor, which is another green solution (ibid., p.17). It is designed for 8 to 20 hours operation, during which a payload of roughly 35 t can be carried. In terms of energy storage, battery packs with a capacity of 132 to 220 kWh are installed depending on the configuration. Another supplier is Orange EV (ibid., p 18). Its electric terminal tractor, the T-Series 4x2, is already in production. With the help of an integrated battery in the range of 80 to 160 kWh, the vehicle should be able to drive up to 160 km without interruption. This model can also carry a payload of up to 37 t. Other battery electric terminal tractors are also entering the market. The manufacturer Mafi developed a green version of the conventionally powered T230, which will be available from spring 2021 (Meyer, 2021). A battery with up to 177 kWh will replace the diesel engine and thus represent another environmentally friendly option. The YT-203, introduced by Terberg in 2020, represents a new generation of fully electric terminal tractors (Terberg, 2020a). It will feature several optimizations compared to its predecessor, which was used in the KV-E-Chain project (see Section 4.1). For example, the new model, which can be equipped with a battery capacity of up to 222 kWh, should offer a significantly higher operating range. Additionally, the drive system consists of fewer parts compared to the previous generation, which results in lower maintenance costs (ibid.). There has also been some progression in the development of terminal tractors with fuel cells, even though they are not yet ready for the market. In October 2020, Terberg started testing a hydrogen-powered vehicle model that has been developed within two years (Terberg, 2020b). As of now, the YT203-H2 is equipped with four 150 l (350 bar) fuel tanks containing about 15 kg of hydrogen. According to Terberg, this vehicle model is capable for full day operations in heavy-duty applications. The manufacturer Hyster is also stepping up its efforts to develop environmentally friendly solutions. The first prototypes of electric and hydrogen-powered terminal tractors are to be realized this year for field testing (Nuernberg, 2020). In addition, other research initiatives will test the feasibility of FCEV in terminal operations in the future. For instance, the H2 ports project will demonstrate and evaluate the use of hydrogen powered yard tractors in the port of Valencia by the end of 2022 (H2 ports, n.d.). Table 10 summarizes the specifications for the presented vehicles.

Vehicle type	BEV	BEV	BEV	BEV	BEV
Product name	BYD 8Y (Q1M)	Kalmar T2E 4x2	Orange EV T-Series 4x2	Mafi T230 E	Terberg YT-203
Battery capacity [kWh]	217	132-220	80-160	177	up to 222
Range	>10 h	8-20 h	160 km	n.a.	n.a.
Payload [t]	37	35	37	n.a.	n.a.

Container handler

In the following, the current developments for both masted container handlers and reach stackers will be described. In the empty container handler segment three different companies, that have a zero-emission version in their portfolio, were identified. The model SCDE90K7 from the Chinese manufacturer Sany will be available for the European market this year at the latest (Cooper Handling, 2020). Accordingly, the vehicle will be capable to reach 7 x 9'6" containers high. The overall weight will be 43 t in order to lift cargo up to nine t (Sany, 2019, p. 1). It uses a Li-ion battery with a capacity of 332 kWh, which provides enough energy for a continuous working shift lasting up to 10 hours (Cooper Handling, 2020). The batteries can be charged in an hour even if this is not recommended by the producer as a routine. Moreover, the battery efficiency will reduce to 80 % after 4,000 charging cycles. Regarding the technical design, the vehicle contains three electric motors, which provide a peak power of 600 kW. The batteries are located at the rear, so that they also act as counterweight. With regards to the performance, travel speeds are limited to 20 km/h, although diesel equivalents reach 25 km/h. Nevertheless, this was on purpose as top speed does not have a major impact on container productivity, unlike acceleration. The electric version reaches top speed in eight seconds, which is four times faster than the diesel version (ibid.). The second manufacturer is Kalmar, which offers two versions, which differ in terms of their lifting heights (Kalmar, 2018c, p. 6). The first version can lift up to seven m high, whereas the second one reaches 10 m. In terms of the lifting weight, both are capable to move cargo up to seven t. With regards to the vehicle mass amounts to up to 30 t.

Moreover, there are two batteries installed. Each has a weight of 3,290 kg and together they provide energy of 260 kWh at five hours discharging. With Li-ion batteries, the charging time is about 100 minutes (ibid., p.4). The third manufacturer XCMG is from China. Its fully electric empty container handler XCH907E weighs 42 t in total (XCMG, n.d.). It is designed to handle cargo up to nine t. This model is equipped with a 350 kWh lithium iron phosphate battery. Unlike the previously presented container handlers, a travel speed of up to 27 km/h can be reached. With regards to the survey-based user requirements, the available options do not achieve the desired lifting capacity of 11 t. In terms of loaded container handlers the first two zero-emission models are integrated in daily operations of the Port of Los Angeles since 2020 (Port of LA, 2020). They are

going through a test phase and initial results are satisfactory according to the executive director. For the Los Angeles port operator, the test phase is another step towards their objective of substituting all cargo-handling equipment with green solutions by 2030. There are two battery electric container handlers, which were designed and built by the company Taylor Machine Works. A battery of 1,000 kWh is installed in the vehicle that enables it to work up to 18 hours between charges (ibid). These container handlers can be recharged in two hours in order to transport weights up 41 t (Cal-Lift, 2019). Another research project has been testing the performance of battery electric container handlers in the port of Long Beach in the USA since 2019 (C-Port, n.d.). Three battery electric top handlers with a 931 kWh battery pack were developed by Taylor Machine Works and BYD for this reason. Furthermore, manufacturer Hyster develops two electric container handlers for demonstration projects in the port of Los Angeles (Hyster, 2019). The first is solely powered by a Li-ion battery. The manufacturer states, that a battery-only approach will not be suitable for larger fleets due to the high electricity demand. In addition, complications could arise when multiple trucks are charged at the same time. Thus, Hyster also develops a loaded container handler with an integrated fuel cell. Planning complexity as well as charging events are reduced by the use of hydrogen. According to Wilcox, this research platform consists of a 200 kWh battery pack as well as a 90 kW fuel cell and 20 kg H2 storage at 350 bar (2019, p. 7). Regarding reach stacker configuration, Hyster also develops a hydrogen-powered reach stacker in the port of Valencia in the course of the H2 Ports project (Hyster, 2019).

Moreover, Chinese manufacturer XCMG launched a fully electric reach stacker and mass production has already started due to the high market interest (Shoko, 2020). The energy for the vehicle XCS45-EV is provided by a 235 kWh battery. It is designed to operate for eight hours and has a lifting capacity of 45 t. For instance, it is already in operation in a terminal in Shanghai without any breakdown after more than 2,000 operating hours. In each shift the vehicle handles 200 containers or 500 t of bulk cargo (ibid.). Table 11 summarizes the results from the market analysis for this vehicle platform.

Vehicle type	BEV	BEV	BEV	BEV	BEV
Configuration *	ECH	ECH	ECH	CH	RS
Product name	Sany SCDE90K7	Kalmar ECG70-35E4	XCMG XCH907E	Taylor ZLC976 (testing)	XCMG XCS45-EV
Range [h]	8-10	n.a.	n.a.	up to 18	8
Lifting capacity [t]	9	7	9	41	45
Vehicle weight [t]	43	30	42	n.a.	n.a.
Battery capacity [kWh]	332	260 (at 5 h discharging)	350	1,000	235
*			Empty Container handler = ECH, Container handler = CH, Reach stacker = RS		

Shunting locomotive

The first battery electric shunting locomotive was the NS 999. The development started in 2007 and seven years later, the manufacturer worked on the next generation with an optimized design (Norfolk Southern, 2014). Despite intense testing, the prototype of the NS 999 never met the requirements in order to be put into service (Corselli, 2020). As a consequence, the project was abandoned and the prototype was offered for sale. It was recently acquired by the company RPS, which is specialized in modernizing rail vehicles. By replacing the power control systems among others, the zero-emission prototype has been further updated and will be tested in a rail yard in California. The manufacturer Progress Rail also developed an emission-free solution. Last year, the Li-ion battery shunter EMD Joule went into a pilot phase in Brazil. Its battery pack has a storage capacity of 1.9 mWh. According to the manufacturer, it is intended to make the new switcher locomotive globally available in early 2021 (Progress Rail, 2020a). Furthermore, Progress Rail will supply the same kind of battery electric shunting locomotive to the freight operator PHL (Progress Rail, 2020b). It is intended to be used for a demonstration project in the ports of Los Angeles and Long Beach. For this application, the locomotive is can provide 3,200 hp or roughly 2,400 kW and will be tested starting in the third quarter of 2021. The battery capacity is 2.4 mWh in order to work up to 24 hours. In the same ports, another demonstration project is carried out. In the course of the program Zero-Emission Track-Miles Locomotive, a 1,600 kW shunter with a battery capacity of 2.89 mWh is being built (BAAQMD, 2019, p. 72). It was expected to run the testing phase in 2020. Already more than 10 years ago, a hydrogen-fueled prototype of a shunting locomotive was developed (Miller et al., 2011, p. 1ff.). With regards to the technical design, the total weight was 130 t. The lead-acid battery in combination with the fuel cell allowed a maximum power of 1.5 mW for about five minutes. During the testing phase in 2010, it was demonstrated, that the onboard energy storage is sufficient to operate for 11 hours. Operating as a single-unit locomotive, trains with masses between 180 to 1,600 t could be pushed and moved. All in all, demonstrations have shown, that shunting operations with fuel cell are technically feasible. This is also stated by another feasibility study by the companies Ballard and Latvian Railways (Pocard, 2018). The project partners came to the conclusion, that fuel cell propulsion is technically feasible in order to meet all requirements in terms of weight, space and operational issues. Despite these positive results, no further development for shunting trains with heavy load requirements can be found. At smaller scales, the University of British Columbia intends to demonstrate a hydrogen storage retrofit solution on a shunting locomotive with about 700 hp (Mitacs, n.d.). The project is expected to be completed by 2022.

Vehicle type	BEV
Product name	EMD Joule
Battery capacity (kWh)	2,400
Peak power (kW)	2,400

Road-rail vehicle

For the road-rail vehicle, there are already several suppliers producing emission-free solutions. For example, the German manufacturer Zagro offers seven variants that differ in terms of their size. Battery-driven road-rail vehicles with a maximum tractive capacity in the range of 50 to 2,000 t are covered (Zagro, n.d.). The smallest vehicle variant has two 115 Ah/ 12 V batteries, which corresponds to about three kWh. The largest variant is the Zagro E-Maxi XXL. It has a total weight of 24 t, which is distributed over the dimensions of H 4865 x W 2500 x H 3450 mm. According to the manufacturer, a mass of up to 2,000 t can be towed at a speed of up to 19 km/h. For power supply, this model is equipped with lead-acid batteries of 2000 Ah / 80 V, which is the equivalent of about 160 kWh. Likewise, there is the E-Maxi XL variant, which could handle up to 1,000 t towing weight. Therefore, it could meet the requirements of the ports from the InterGreen-Nodes project. However, according to the supplier, this specification only applies to level-even tracks. The company Zwiehoff, whose conventionally-powered road-rail vehicles are used at the facilities of the InterGreen-Nodes project partners, also offers two BEV in this segment. The largest variant ROTRAC E4 has a weight of 7.5 t, which allows the vehicle to tow up to 500 t of trailer load. With regards to energy supply, it is powered by 930 Ah / 80 V batteries, which corresponds to a capacity of approximately 75 kWh (Zwiehoff, n.d., p.2). According to the manufacturer, eight operation hours can be realized in one charge. As the towing capacity only reaches a maximum of 500 t, Zwiehoff currently does not offer green solutions that meet the requirements on towing capacity derived from the survey.

In addition, the manufacturer Zephir produces battery-powered road-rail vehicles (Zephir, n.d.). Its product line covers towing capacities from 600 to 2,600 t. The model 7.90 E for example, has a total weight of 16 t and is capable to transport up to 1,400 t. The maximum speed for this model is seven km/h. The heaviest variant manufactured by Zephir has a service weight of 24 t to move weights up to 2,600 t. Each variant is powered by lead-acid batteries with a capacity of 2 x 960 Ah / 80 V or 154 kWh. The last company to be mentioned is Colmar. Among other variants, this company manufactures the most powerful electric road-rail vehicle to date (Colmar, n.d.). The SL1600E has a total weight of 30 t and can tow 3,600 t. The three battery packs provide a total capacity of 4200 Ah / 80 V or 336 kWh. According to the manufacturer, this allows for at least eight hours of operation. In summary, from a technical point of view, there are several existing solutions, which could meet the requirements of the surveyed ports (see Table 13). For example, various models are offered as battery-driven configurations with towing capacities above the required 1,000 t by different manufacturers. There were no literature and reports about hydrogen-powered road-rail vehicles. Due to the usually short ranges, production of this drivetrain configuration is unlikely.

Vehicle type	BEV	BEV	BEV	BEV	BEV	BEV
Product name	ZAGRO E-MAXI XL	ZAGRO E-MAXI XXL	Zwiehoff Rotrac E4	Zephir 7.90E	Zephir 13.90 E	Colmar SL160E
Weight [t]	16	24	7,5	16	24	30
Battery capacity [kWh]	n.a.	160	75	154	154	336
Towing capacity [t]	1,000	2,000	500	1,400	2,600	3,600

6.3. Economical assessment

As already pointed out, zero-emission vehicles are characterized by significantly higher acquisition costs compared to conventionally operated vehicles. This issue will be examined in more detail in this section. In the literature, data on prices can be found for a selection of vans and terminal tractors, which are shown in the following table.

Zero-emission Transporter (3.5 t)					
Product name	Iveco Daily Electric	VW E-Crafter	Mercedes eVito	Renault Master Z.E.	Renault Master Z.E. Hydrogen
Base price [€]	~ 70,000	~ 82,747	~ 47,588	~ 59,900	~75,000

| Zero-emission Terminal tractor		
Product name	BYD 8Y (Q1M)	Kalmar T2E 4x2	Orange EV T-Series 4x2
Base price [€]	~ 250,000	~ 225,000-290,000	~ 165,000-235,000

The cheapest BEV model for the van in this selection is the eVito from Mercedes-Benz at just under 48,000 €. The VW E-Crafter shows, that prices of up to 83,000 € can also be called up by the manufacturer. At 75,000 €, the FCEV variant of the Master Z.E. is about 15,000 € more expensive than the battery electric version. Compared to diesel-powered vehicles, the prices are substantially higher. For instance, Schlosser et al. reveal a price gap in favor of diesel variants (2019). They matched an electrified light commercial vehicle with its diesel brother of the same brand. As a result, the purchasing price of the BEV was 67 % higher. Moreover, they found that this example is not a unique case but a consistent pattern for the market segment (ibid.). Additionally, the purchase costs for a vehicle of this class also differ from the expectations of the project partners. According to the survey, the upper boundary for the highest acceptable purchasing price was just under 50,000 €. This price limit is exceeded by the most of base prices of the presented vehicles, although they cannot even fully meet the technical requirements.

Battery electric terminal tractors are available from a price of around 165,000 €. The majority is in the price region of about 250,000 €. This is in line with the statement of Sisson, who also mentions $300,000 as a typical expense for electric terminal tractors (2017, p.68). These prices are from companies that produce in very small quantities. Thus, greater demand could lead to more companies developing green solutions, which would lead to greater competition and reduced prices. Likewise, assembly line production could be implemented, which results in cost savings and therefore a lower sales price. At the present time, the purchase price of a diesel tractor is much lower. They cost around $125,000, which is equivalent to 100,000 € (ibid.). In terms of the expectations of the InterGreen-Nodes project partners, the respective prices for electric terminal

tractors are again above tolerance limit. Koper indicated a maximum purchase price of 200,000 € and for Budapest a price above 250,000 € is too expensive. The biggest discrepancy is for Bologna, which only tolerates a price of about 100,000 €. The purchase price for BEHALA's electric road-rail vehicle, whose operation is described in more detail in Section 6.1, was around 250,000 € according to the operations manager. It is more than twice as expensive as the upper limit of Interporto Bologna, which is 120,000 € according to the survey. Although no precise data is available for zero-emission models of the other vehicle platforms, it can be assumed that electric alternatives are currently significantly more expensive compared to similar diesel variants in terms of their acquisition costs. Thus, purchasing costs are another inhibiting factor that prevents terminal operators from integrating green vehicles into their fleet.

However, costs might decrease in the future due to economies of scale as well as optimization of vehicle components. This would particularly impact the cost of the battery, which is a key factor in the purchase price. Goldie-Scot illustrated the average prices for Li-ion battery packs in passenger vehicles over the years (2019). From 2010 to 2018 the price for one kWh dropped from about $1,160 to $176. Furthermore, a forecast until 2030 was made. Based on this observation, a further decrease to $94/kWh in 2024 and $62/kWh in 2030 is expected. Nevertheless, these prices cannot be realized for the commercial segment, as vehicles with battery and fuel cell drives are often conversions and not manufactured in serial production (Altenburg et al, 2017, p.66). Thus, although a significant price reduction is still expected by 2030, it will decrease more slowly than in the passenger car segment. In the commercial vehicle segment the battery prices were 700 to 1,000 €/kWh in 2015 (ibid.). This is in line with Michalk, who indicates 500 to 1,000 €/kWh (2018, p.20). By 2030, prices are expected to drop to between 200 and 285 €/kWh (Altenburg et al., 2017, p.66). Figure 16 shows battery costs for capacities up to 3,000 kWh based on the 2015 price and the 2030 forecast.
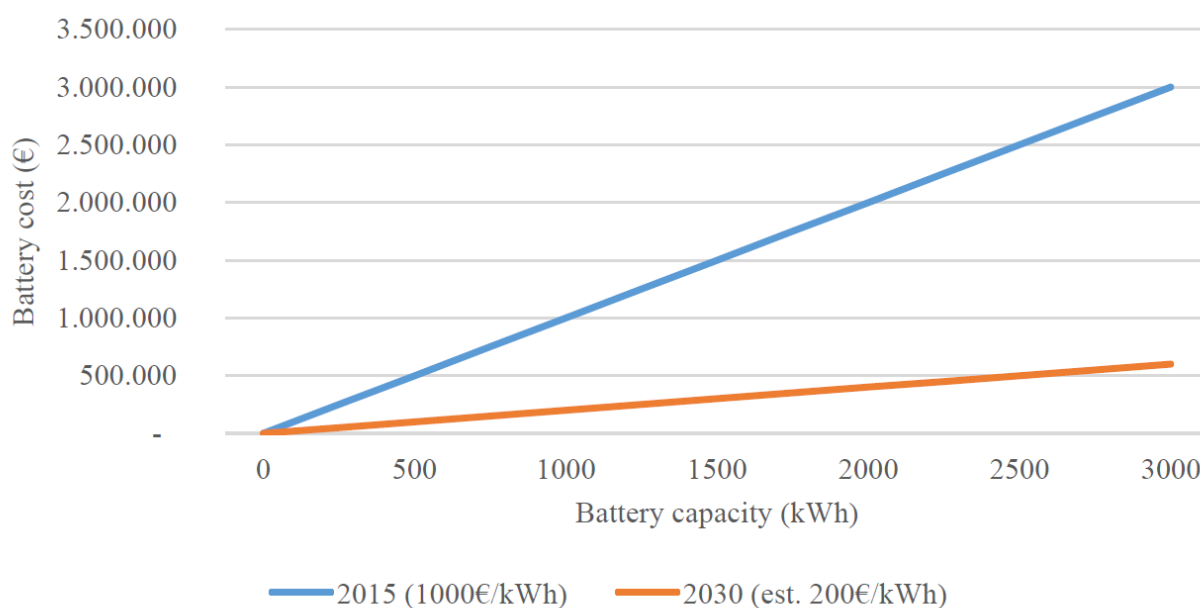
The battery of a shunting locomotive with a capacity of 2,400 kWh would therefore cost 2.4 million €. In this case, the battery price alone would be higher than the maximum acceptable purchasing

price specified by the participating ports. In the survey, Koper and Bologna stated, that an electric locomotive with a total price of 1.7 to 2.2 million euros would already be too expensive overall. In 2030, the battery with the same capacity would cost only 480,000 €. The empty container handler serves as another example. According to price data from 2015, the battery of 300 kWh would cost 300,000 €. In comparison, the port operator from Berlin purchased a diesel-powered empty container handler for 250,000 € in 2014. With the 200 €/kWh expected in 2030, the battery costs for a capacity of 300 kWh would decrease to only 60,000 €. An electric version of this vehicle platform could then approach to the price level of its corresponding diesel variant.

The fuel cell cost about 2,000 €/kW in 2015 and is expected to be 100 €/kW in 2030 (ibid). In addition, the price of the H2 tank is expected to decrease from 1,000 to 300 €/kg during this period. Currently, FCEV are even more expensive than BEV, as the latter profits from a greater market maturity. Morrison et al. predict, that costs of FCEV and BEV will converge by 2030 (2018, p.183). Even though forecasts always have to be considered with caution, they prove the trend that component costs will decrease significantly in the future. This would close the economic gap to conventionally powered vehicles and therefore lower the obstacles to the use of green solutions.

7. Conclusion

In the present work, user requirements for six vehicle platforms were determined from terminal operators with the help of a survey. On this basis, special vehicle manufacturers can be contacted in order drive forward the development of green transport solutions. Moreover, a market analysis identified existing solutions with battery electric drive for almost all considered vehicle platforms. With regard to fuel cell powered vehicles, options could be found only for the transport van, which indicates a low level of development. This drivetrain concept is currently being tested in pilot projects for container handlers and terminal tractors, whereas no development could be found for rail-bound vehicles. Even though many more battery electric models are available on the market, some of them are not able to meet the desired operating conditions of the InterGreen-Nodes project partners. Especially in the case of the transport van, considerable restrictions are to be expected. In comparison to diesel fueled vehicles, the performance gap for this platform can be narrowed with fuel cell propulsion. The situation is different for mooring vehicles, which also have a total vehicle mass of 3.5 t like the transporter. Since mooring application offers more space for a larger battery weight, battery-powered propulsion is also considered appropriate for trip distances of about 200 km. With regards to terminal tractors, multiple manufacturers offer BEV that could match the requirements of the surveyed project partners. For longer ranges, hydrogen fuel cell models are being tested, which are capable of operating a full day. In case of the road-rail vehicle, an integration of a fuel cell system is unnecessary due to the short range requirements. This aspect is underpinned by the exclusive availability of green solutions with a battery electric configuration in this vehicle segment. In the present study, the container handler with up to one mWh as well as the shunting locomotive with about 2.4 mWh represent the vehicle platforms with the largest energy requirements. As previously described, even manufacturers of battery-powered container handlers point out, that the power grid could be overstressed if multiple vehicles are charged at the same time. Likewise, a high charging capacity is needed in order to recharge the vehicles within expected time frame. Therefore, the respective infrastructural conditions must be taken into account when selecting the energy source. At the present time, the purchase costs for environmentally friendly solutions differ from the expectations of the surveyed terminal operators. For example, variants already exceed the financial limits of the project partners, even before the technical requirements are met. Nevertheless, this obstacle is expected to be overcome in the coming years due to cheaper system components for both battery and fuel cell.

Last but not least, the validity of the present study is critically reflected. Technical properties based on the survey are only rough estimates. For instance, it was decided to use simple methods with several simplifications for assessing energy demands. Relevant parameters for the simplified calculation of battery dimensioning were mainly the desired range and the vehicle gross weight. Additional influencing factors such as temperature, the explicit route profile or driving behavior were not taken into account, as this would have been beyond the scope of this thesis. Especially the results obtained for the container handler need to be treated with caution. First, they are based on a fictitious process and second, the used formulas do not consider resistance and efficiency losses or other auxiliary units. In this respect, a general safety margin of 10 % was added, but this amount is just a mere heuristic and not based on validated facts. Furthermore, some of the survey-based user requirements for the vehicles must be cross-checked again and

possibly revised. In some cases, expectations were placed on electric vehicles that could not even be fulfilled by conventionally powered vehicles. It is also worth mentioning that expectations for alternative fuel vehicles are lower if terminal operators have already been gained experience with such models. This is particularly evident in the range specifications for the terminal tractor. While Berlin specified 40 km for this vehicle platform, Koper and Bologna defined a desired range that is ten times higher. In summary, the present study provides an initial orientation on technical and economic characteristics for the respective use cases. However, the results must be validated once again under greater consideration of the individual framework conditions, under which the vehicles are operated. Under any circumstances, extensive testing of these vehicles must take place.

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