Assessing E-Vehicle Utilization in Supply Chains

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Assessing E-Vehicle Utilization in Supply Chains

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***Abstract*—Greener electrified transportation is increasing in popularity while many questions remain in the usage abilities of the electric vehicles. Currently, one of the greatest challenges in the usage of electric power is in battery charging. In comparison to fossil-fuel-based engines that can be refueled in minutes, the charging of an electric battery can consume considerably more time. Different solutions to energize the electric vehicles have been proposed, however the holistic evaluation of the practical feasibility remains relatively unexplored in different solutions. This paper discusses recent development and key aspects and their impact on heavy transportation logistics. The results illustrate a comparative analysis about different energizing solutions' impact on logistics processes in two supply chain cases. The contribution of the paper allows a holistic view of different charging solutions and their suitability for road logistics supply chains, thus enabling better management of the transformation towards the possibility of using electrified logistics.**

***Keywords*— assessment, battery swap, cost, electrical vehicle charging, end usage, e-trucks, feasibility, road transportation.**

I. INTRODUCTION

The increasing number of e-vehicles has been estimated for two decades in the transportation sector [1]. As an intermediate step the hybrid-vehicles have become more common. However, they have not been considered as a long-term solution to the underlying problems such as the energy crisis, the low energy efficiency of conventional vehicles, as well as the emission they produce [2]. Indeed, environmental issues are arguably the most important driver, which can be seen to drive the change towards e-vehicles in different aspects. The environmental consciousness in the society is building pressures towards the business in the field as well as decision makers who are responsible for regulation.

While debates about the climate change and overall relevance of sustainability in business are still ongoing, the change towards more environmentally friendly e-vehicles is occurring in different pace in different regions. EU is one of the most strict regions in terms of environment protection. In terms of e-vehicles, however, China has had the most advancement [3]. China as one of the worlds most populated countries has experienced pollutions caused by fast economic growth and increased popularity of living standards and vehicles. According to a report, vehicle emissions contributed to 52.1% of the source of fine particulate matter air pollution in Shenzhen for example [2].

In Finland the popularity of e-vehicles is still quite modest and especially in the logistics sector. Only a few e-trucks are utilized (see Fig. 1). The share of e-vehicles from overall road transport sector was only 0.5% in 2021, while the goal for 2030 is set as high as 40% [4]. In terms of logistics, Finland is a particularly challenging country for e-vehicles, with sparse population, long winter time and long distances. All these factors have to be taken into account when planning the utilization of EVs. Compared to conventional diesel powered trucks, e-trucks lack the infrastructure and, in many ways, are more difficult to operate efficiently in long distances. Indeed, an efficient routing of e-vehicles has been identified as a challenge in the previous literature, requiring the planning of recharging time, with additional labor and costs involved [5]. Scholars have argued that there is still a long way to go before e-vehicles can become a dominant way of transportation [6]. It is clear that several challenges still remain in the logistics sector and hinder the use of e-vehicles in transportation. Further research is then needed. While some research is also conducted about the use of e-vehicles in the last mile deliveries, more research is needed to study the feasibility of e-vehicles in longer distances.

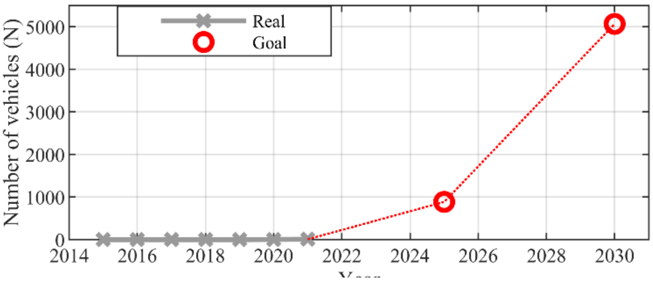

Fig. 1. E-trucks numbers in Finland. The red dot denotes goal of usage [4].

The aim of this paper is to investigate the state-of-the-art technology in electric trucks and how it could be utilized in the case of supply chains. More precisely, two case supply chains are presented with single mode and intermodal transportation, respectively. The paper identifies the underlying conditions which are needed for the use of e-vehicles (EVs) in the cases. The paper furthermore discusses the impact of delivery time, necessary infrastructure and costs using two different technologies, namely battery recharging and battery swapping.

II. THEORETICAL FOUNDATION

A. Current state of battery powered trucks

The battery swapping and high-power charging are not mutually exclusive but complementary. NIO and Geely are offering battery swapping systems for passenger class EVs. The battery swapping technology is great alternative for high power charging specially to support long distance travelling. According to NIO it takes only 3 minutes (min) to swap a fully charged battery into NIO's ES8. The NIO's 2nd generation (2021) battery swapping is fully automatic, and the EVs can automatically maneuver into the station. In the NIO's service the user can also upgrade of downgrade the size of the battery pack. 70 kWh, 75 kWh and 100 kWh long range battery packs are available in the service. The 100 kWh long range battery pack gives an estimated 580 km range according to New European Driving Cycle (NEDC).

In the trucks and off-road heavy working machinery the battery swapping system is even more compelling than in the lighter vehicles. In the heavy transportation the EVs should be running 24/7 and the battery charging time is taken aways from productive time.

B. High power charging

High power charging requires the charging power electronics off board of the EVs. The interface between the charger and the EVs should use direct current (DC). Then an EV does not have to carry bulky charging converters and more realistically, there is no room to accommodate the charging converters onboard. Thus, the charger or charging station must output DC power at their terminals to the EVs.

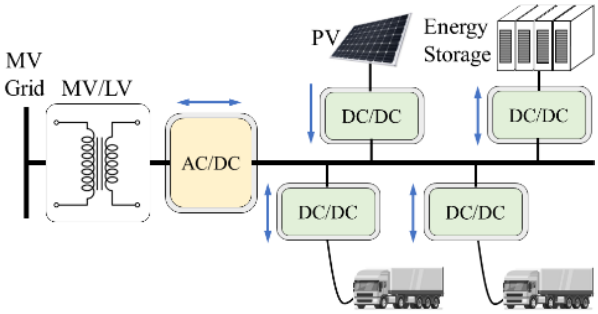

Fig. 2. DC system configuration for high power charging stations

In a charging station, the electrical system can be AC or DC. Unlike the AC system, a DC system has a DC bus to distribute power to the terminals. As shown in Fig. 2, the system is simpler. The DC voltage is obtained from a central AC/DC rectifier after the line-frequency transformer. The DC bus can also be directly fed with renewable energy sources. For high power charging, energy storage is likely to be used for mitigating the charging influences on the grid. Then the energy storage can be connected to the DC bus via only a DC/DC converter. For obtaining high power, the chargers usually connects multiple identical modules in parallel to output sufficiently large currents [7]-[9].

The leading high power charging station products on the market in 2022 are summarized in Table I. Commercial MW level chargers have not yet been available on the market. A few power electronics suppliers are working towards this level of high power. Regarding the outlet type, CCS has higher power ratings than CHAdeMO. The power unit of the charger is always modular so that high power can be achieved with multiple modules. The most used module power is 30 kW (DC output). If aimed at passenger cars and trucks, the cable of the dispenser is liquid cooled. The ABB and Power Electronics models have pantograph arm options for electric buses.

The highest power level to date on the market of charging stations is 600 kW. The input AC voltage is always 400 V to fit the low voltage distribution network. The DC output allows for varying voltage to meet different battery demands. The operating temperature can be low enough for Finland without power derating. Degradation of output occurs only at high temperatures. The power factor and efficiency look high enough at full load. Their partial load data is not available in the published datasheet. We see two directions that lead to boosting the power from 600 kW to MW. One is to add more modules based on current products. The other is to explore and apply new technologies and possibilities, such as a higher input AC voltage, using an SST and new converter topologies. EV charging from hundreds of kW to the MW level is enabling a step forward for power electronic technologies. From the experience of Norway, the fast charging stations are extensively equipped with 250 kW chargers. Chargers of 600 kW have not been widely deployed.

In a typical high power charging system, multiple charging sockets are available, but full charging power is only available when a single socket is used. For example, in Heliox system with 1 MW charging power, only 360 kW charging power is available for 3 vehicles and 180 kW for 6 vehicles. This kind of distribution of charging power might have a big influence on the charging time during the peak hours. In planning of driving routes, these uncertainties cause big problems.

C. Battery Swapping

Heavy-duty electric trucks can also be powered by battery swapping technology. This technology is rapidly developing in China because of governmental policy supports and the success of electric passenger cars on this market [18]. As illustrated in Fig. 3, the sales share of battery-swapping electric (BSE) trucks in the battery-electric truck market increased from 20% in January 2021 to 47% in September2022 [19]. China has started pilot projects in three cities: Tangshan, Baotou and Yibin which cover the north and south of China. For example, Tangshan intends to deploy 2600 BSE trucks [20]. The application stays mainly within 200 km, such as logistics hubs, industrial zones, mines and ports as well as road-railway connections. Battery swapping significantly reduces the offline time of the electric trucks. Truck manufacturers e.g., CAMC, Hongyan, have entered the BSE truck market for years, and some of them, e.g., SANY, sells both BSE trucks and battery swapping stations. Specialist companies, e.g., Enneagon Energy, Bozhon, supply the battery swapping/charging solutions.

Battery suppliers, e.g., CATL, Harmontronics, are also developing battery swapping solutions for BSE trucks in addition to electric passenger cars. CATL says their batteries have been deployed to 90% of the BE trucks and off-road machines in China. This market share facilitates CATL to establish standardized battery swapping stations.

Outside of China, however, there have been few experiments with battery swapping technology. As a result of high capital cost and low consumer demand, early commercial attempts to promote battery swapping by Better Place and Tesla did not achieve success [21]. Chinese e-truck manufacturers export BSE trucks to the world. For example, XCMG electric vehicle fleet (E700) and its battery swapping stations have been exported to New Zealand through Etrucks [22]. The E700 battery powered truck has a 282 kWh battery pack which can be fast charged in three hours or swapped under five minutes. It can run within 100 to 200 km range depending on the load, route and other conditions.

1) Technology

Unlike passenger cars, BSE trucks change the battery by top-hanging or side-inserting. Top-hanging is most used in China due to its simplicity. The most used battery pack for BSE trucks is the 282-kWh lithium-iron-phosphate battery supplied by CATL. Bigger batteries of 350 kWh and 450 kWh levels are being deployed [23], e.g., the 423 kWh CATL battery. In addition to battery swapping, the BSE trucks can also be charged at DC charging stations. According to the truck manufacturers' data, the mileage can reach 150-170 km [24] or over 180 km [25] with a fully charged battery pack. The battery swapping time is less than 6 min and the

TABLE I. LEADING HIGH POWER CHARGING STATION PRODUCTS ON THE MARKET IN 2022

Make	**ABB** [10]	**EVBox** [11]	**Efacec** [12]	**Heliox** [13]	**Ingeteam** [14]	**Power Electronics** [15]	**CirControl** [16]	**Kempower** [17]
Model	Terra HP 350	Troniq Modular	HV350 G2	Ultra-Fast	INGEREV RAPID ST400	NBp	Raption 350 HPC	C803
Power (kW)	350	240	350	600	400	600	350	600
Output	500 A, 150-920 V DC	500 A, 150-920 V DC	920 V DC, 380 A, 500 A up to 700 V	460-800 V DC, 600 kW, 1 kA max. bidirectional	50-1000 V DC, 500 A up to 500 V, 400 A up to 1000 V	150-1000 V DC, full power from 300 V	150-920 V DC, 500 A	200-920 V DC, 652 A at 920 V
Power factor	>=0.97	>0.99	>0.98	0.99 above 50% rated	Adjustable 0 – 1 (lead/lag)	>0.99	>0.98	0.92 at full load
Efficiency	>=94% at full load	95% peak	>95%	96% peak	Unknown	95%	95% at nominal power	94% at full load
Weight (kg)	2380	680	2712	5100	1560 + 530	Unknown	440	1080-1200
Operating temperature range	-35 ~ +40ºC, no derating	-25 ~ 40ºC, no derating	-25 ~ 50ºC	-30 ~ 50ºC	-20 ~ 60ºC	-30 ~ 50ºC	-10 (optional -30) ~ 50ºC	-30 ~ 50ºC

battery's charging time is about 1 hour [24]. The highest speed of the BSE trucks is no more than 90 km/h [22]-[24]. Intelligent battery swapping robots have been used, for example, for Yangshan Port in Zhoushan, China. The battery swapping solution is supplied by Enneagon Energy. It takes 6 min to complete the swapping of a 5.5-ton battery pack for an automated guided vehicle (AGV) [26].

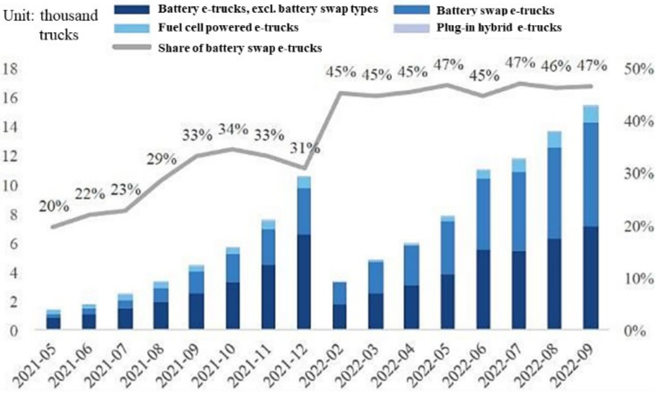

Fig. 3. Development of sales share of different types of electric trucks in China. Reproduced from [19].

2) *Challenges*

In battery powered vehicles the climate and weather conditions play a big role. The pilot projects in China successfully demonstrate the battery swapping technology in cold conditions, e.g., -30ºC. However, the details are not known and how well the battery and stations operate in the cold conditions have not been published. The experience of China can guide the application of BSE trucks in Finland, but more data is needed to prove the technology meets the cold climate of Lapland, Finland in winter. Battery and vehicle heating systems should be developed to solve the potential problem. Furthermore, the pilot projects in China only cover the 200-km-range applications. Longer transportation, such as Helsinki-Oulu (600 km), may need multiple battery swaps or combination of battery swapping and high-power charging.

Another issue is the absence of international standards for battery swapping for heavy trucks. China is establishing provincial-level local standards of battery swapping stations for e-trucks. In provincial level, Nei Mongol has published the first local standard "Electric medium and heavy truck sharing battery swap station and technical specification of battery swap system" (T/IMAS 052-2022) in China [27]. EU has the IEC 62840 standard "Electric vehicle battery swap system" for electric vehicles, not specialized for BSE trucks. Without a standard, battery swapping may encounter compatibility issues. In [28], the battery swapping service fee in China for calculating was assumed to be CNY0.7 per kWh (~EUR0.1 per kWh), including battery leasing and swapping. Scenarios of higher fees are also studied to show how many years of operation will beat conventional diesel-powered trucks. It is certain that the fee will be much higher in Finland and Europe.

D. *Transformation to e-vehicles*

The transformation to e-vehicles in transportation logistics has been an increasing trend in many countries during the previous decade. The necessary conditions for the technology transformation from traditional fossil fuel powered trucks have developed considerably, and in many cases the technology readiness level is reaching the critical maturity to be competitive [29]-[31]. The transformation from traditional technologies to new solutions in a highly competitive field such as logistics can be challenging as the investments are typically relatively high, and there can be high uncertainty about the usability and reliability of the technologies. Indeed, various decision-making techniques have been proposed in literature [29]. The previous research has focused on the last-mile-delivery part of the supply chain, or urban logistics and the study of long-distance utilization is still in its infancy [32]. Especially, when considering the technological advancements done in the last two years in the battery technologies the implementation of fast charging and battery swapping solutions can provide solutions in green transformation for the road transportations.

III. CASE EXAMPLES OF ENERGIZING E-VEHICLES

Besides the technological advancements, the current regulative, political, and social environment is driving a fast change towards non-fossil-using solutions in logistics. Although, in many ways the implementation of e-vehicles is pressured and planned from policy makers in the supply chains, there are still insufficient evidence and too high levels of uncertainty regarding the technology. This paper aims to answer this challenge in the current literature by providing an explorative case study about the different aspects of using e-vehicles in the single and intermodal logistics cases. The study is based on integrated state-of-the-art literature review and empirical and illustrative case example [33]. The empirical part of the study is based on discussion with five industry experts from both logistics field and technology suppliers. The informants were selected to have differing positions in the field to ensure a holistic view to the phenomena. By triangulating between literature, industry experts and the empirical case, the researchers were able to identify key aspects of the e-vehicle implementation and build an illustrative example and analysis of the key determinants in the e-vehicle supply chain.

Two case supply chains are illustrated between Helsinki main terminal and Oulu terminal which can be seen from Fig. 4. The first row of the upper and lower subfigures illustrates the logistics process of the supply chain comprising from an intermodal steps that begins with the loading of the intermodal e-vehicle unit and carriage distance of 130 km between Helsinki and Kouvola. At Kouvola Rail and Road Terminal (later RRT) the transported 2 TEU (Twenty-foot Equivalent Units) container is first unloaded from the e-vehicle into the container yard for storage from which it is loaded into rail transportation comprising of 50 TEU's for 466 km to Oulu rail terminal, from Oulu rail terminal the container is again unloaded from the rail transportation to e-vehicle to be transported for 50 km to the final destination at Oulu region. The second and third row of the upper and lower subfigures illustrate two scenarios for loading the EVs. By using battery recharging with fast recharging technology the e-vehicle is able to do maximum distance of 260 km which is gained by a conservative estimation of typical manufacturer values taking into account winter conditions. The battery recharging time of 100 min is again gained by using typical manufacturer values with the assumption that the battery is full in the beginning and not used under 20% of charge.

In this intermodal process the EVs can carry-out one roundtrip between Helsinki and RRT with full charge and then it is necessary to charge the battery. It is assumed that the truck does have containers onboard for both directions, and battery charging is available in both ends in necessary. The second scenario in the intermodal process utilizes battery swapping technology where only one 130 km leg can be travelled before the battery has to be changed due to the limited capacity of the battery. The differences of using the different technologies are apparent especially when considering the amount of time spent per stop as well as the amount of stops necessary for recharging. In addition, the costs of utilizing the technology are still somewhat unclear, as only few pilot cases exist currently. Some information about the investment costs can be found from the manufacturers, however both the operational costs are still somewhat unclear. In this paper, we aim to present estimations about the investment costs, operational costs for the case supply chains, as well as the necessary infrastructure costs.

One of the limiting factors in road transport logistics is the driving time legislation. In general, the EU legislation allows a driver to drive constantly for nine hours per day. This time does not include the time when the EVs in stopped for example loading, unloading or refueling/recharging. Some exceptions to this rule apply, for example, the driving time can be extended to ten hours on two days per week, however the total driving time cannot exceed 56 hours per week or 90 hours per two weeks. During a work shift a driver should have a break, which depends on the working hours; if a driver works between six and nine hours a minimum of 30-minute break should be held. When the length of the work shift exceeds nine hours an unbroken 45-minute break must be held. Furthermore, a driver is entitled to a eleven hours resting time after the work shift [34].

In the single mode case supply chain, as shown in the upper subfigure of Fig. 4, the driving time with average speed of 75 km/h is estimated approximately at 8 hours. With recharging three times, 100 min each, 300 min (5 hours) should be allowed. Battery swapping requires six times during the trip, and a total of 30 to 60 min (1 hour) should be allowed. Overall, if not considering the driving legislation the route can be done in 13 hours using recharging and 9 hours using the swapping technology, in total 4 hour difference. The required infrastructure investments vary greatly, as the recharging requires only three fast rechargers and in battery swapping, minimum of six swapping stations are necessary with suitable distances apart. When considering the driving legislation which requires the driver to have breaks minimum of 15 min (under 15 min is not sufficient time for break) and after four and half hours of driving (or five and half of working) minimum of 45 min break (can be divided into 15 min and 30 min breaks, respectively). In practice, this impacts the battery swapping scenario so that every break should be minimum of 15 min and every other break should be minimum of 30 min, thus the overall break/loading time for battery swapping totals three hours (3×15 min and 3×45 min) and the transportation time 12 hours.

In the intermodal case supply chain, as shown in the lower subfigure of Fig. 4, the driving time estimation is done with lower speed due to shorter distance and relatively lower amount of highway driving from the total distance. For the first road transport leg, with average speed of 70 km/h the driving time estimation is 111 min (1 hour 51 min). In practice, this can be carried out by a same driver with 2 round trips after which resting time is necessary. If the route is done by recharging the e-vehicle, the overall charging time will be 100 min during the shift and another 100 min at the end of the shift. As the battery is expected to be full for the next shift, another 100 min recharge can be added to the overall time. The second leg of the route after rail transport at the Oulu end is calculated by the same 70 km/h average speed, which means 43 min of transport time and 86 min (1 hour 26 min) for round trip. By using recharging, two round trips and one leg can be transported with the expected range (in total 3 hours and 35 min of driving time). After which a 100 min recharging is done. This model requires the recharging station to be available at both ends. Overall, a driver with estimated 9 hours of driving time could do the 6 round trips with intermediate recharging in total 516 min (8 hours and 36 min). With recharge the time totals 716 min and when finishing the shift the battery is not full.

The intermodal transportation with battery swapping technology requires battery swap at the both ends of the first leg.. As the duration of the trip is the same as in the recharge scenario, namely 111 min, a maximum driving time for a single driver doing round trips is 444 min (7 hours, 24 min) comprising from two round trips. While technically the battery swap would only take between 20-40 min, in total 7 hours 44 min to 8 hours 4 min. In practice, the driver breaks lengthen this time similarly to the single-mode scenario. Thus overall the driver is required to take two 15 min breaks and one 30 min break while recharging. In total this adds up to 8 hours 24 min.

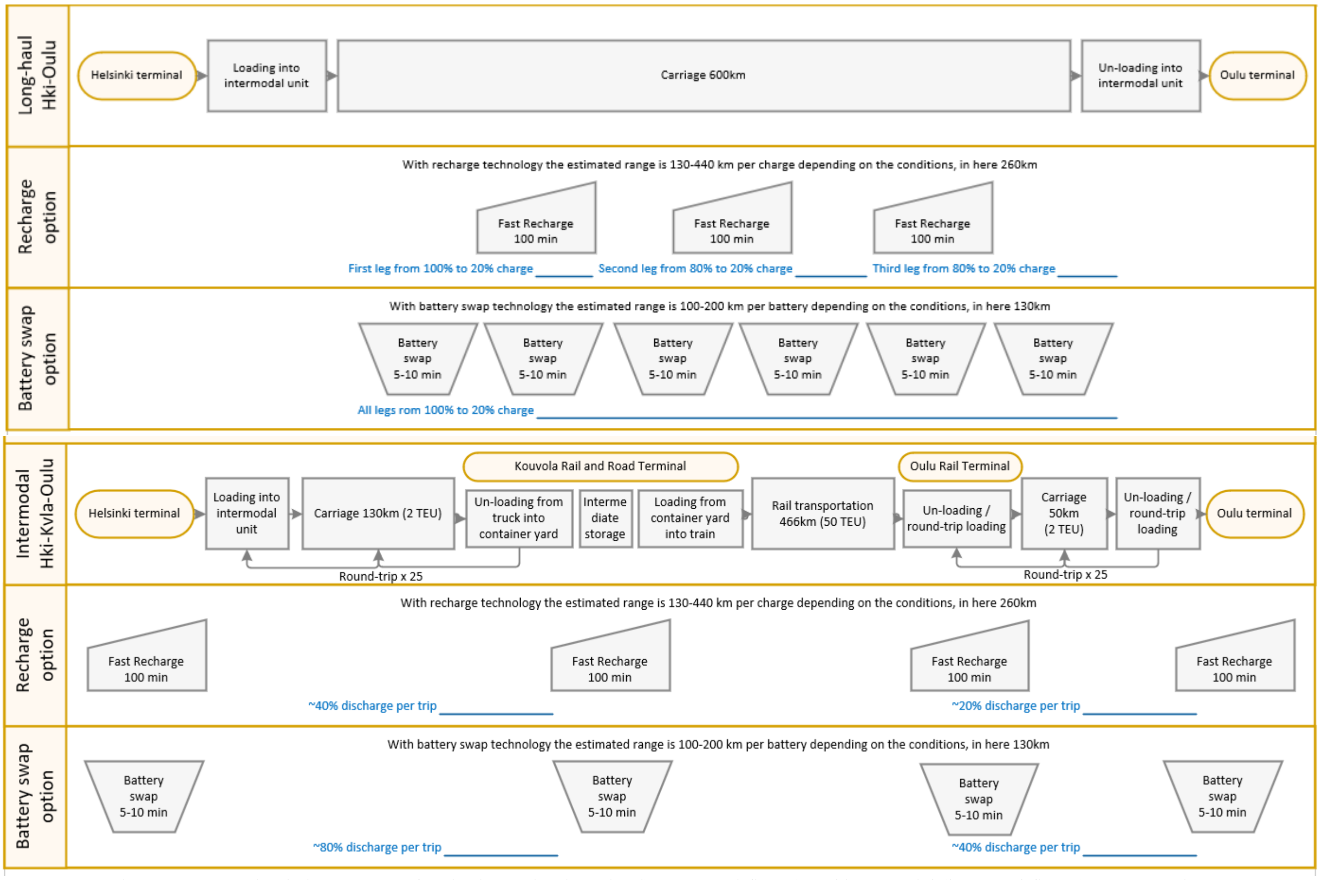

Fig. 4. Case supply chain processes for single-mode (long-haul) (upper subfigure) and intermodal (lower subfigure) transportation.

TABLE II. ESTIMATE OF THE COSTS

	Table column subhead	*Unit Cost*	*Interm-odal*	*Interm-odal cost*	*Long-haul*	*Long-haul cost*
Equipment	Investment cost on e-truck (recharge model)	0.5 M€;	1	0.5 M€	2	0.5 M€
	Investment cost on e-truck (battery swap model)	0.45 M€ (without battery)	1	0.45 M€	2	0.45 M€
	Investment cost on swap battery	0.1 M€ est.	-	N/A	2	0.2 M€
Infrastructure	Investment cost on loading station (battery swap model)	0.5 M€	4	2 M€	6	3 M€
	Investment cost on loading station (recharge) 250 kW	0.05 M€	4	0.2 M€	3	0.15 M€
	Investment cost on loading station (fast recharge) 1000 kW	0.1 M€	4	0.4 M€	3	0.3 M€

The costs related to the case routes are presented in the Table II and divided into investment costs on equipment (for the logistics companies) and infrastructure (for private or public service providers). The operating costs are calculated according to the use as 200 kWh/100 km, but are not presented in Euros due to the high variation in electricity prices, namely due to markets, time of the day and weather. In terms of battery swapping, this can be an advantage as the batteries can be recharged when the electricity is cheapest. It should be also noted that the fast recharging of batteries in the case supply chains is more expensive option than regular charge, but at least four times more time consuming.

It should be noted that driving routes will affect the driving range of e-vehicles and consequently the reported numbers in this section. This uncertainty will be studied in future.

IV. CONCLUDING DISCUSSION

The transformation towards electricity powered vehicles has been the trend for the last years. Many factors, including climate actions and different governmental and regional policies are driving forces behind this. The opportunities offered by EVs have improved during the last years, as the capacity and loading capacities have increased dramatically. The lower weight of the batteries using new technologies have improved the load efficiency in the heavy road transportation and the range offered by them have started to intrigue many logistics companies. Lithium-ion batteries have multiple advantages over lead-acid batteries, the higher energy density and the depth of discharge have influence on the loading capacity of the EVs directly. While the lead-acid batteries can only be discharged around 50% of the total capacity the lion batteries can be used up to 85% during a normal cycle.

Pilot cases about using different battery technologies have been put forward, especially in China. The new battery swapping techniques are clearly providing new opportunities compared to the recharging option as it offers improved utilizations of the EVs. However, several limitations have to be taken into account when estimating the feasibility of these technologies. For example, the range that different options offers might differ significantly. In different scenarios the impact of these might be essential to take into account. Our results illustrate how the difference in operating the EVs in different ways. Firstly, the long haul option is in many instances important in more sparsely populated areas. Secondly, the intermodal option seems to offer more flexibility. Finally, it would seem that as the current range of the EVs vary significantly more studies about their possible use should be carried out.

Most of the current studies investigating the use of e-vehicles focus on the technology rather than taking more holistic supply chain or logistics process into account. As can be noticed from the results of this study the overall limitations for example on the driving time and working hour limitations should we taken into consideration when implementing EVs in the supply chain. Depending on the technology the required breaks and recharging or battery swapping times may be optimized on routes of different length.

The investments required of battery charging or swapping can be considered significant. For companies and decision makers the investments on certain technology in a highly competitive field like logistics can be either competitive advantage or in some cases a death blow. The technology transformation for the utilization of e-vehicles needs to be successful for more than local distribution where loading station can be invested in by the companies themselves or regional authorities. For this purpose, comprehensive collaboration and wider regional strategies should be considered. Currently, the strategies regard transferring to the e-vehicles remain only in the levels of goals how many e-vehicles should be in use by certain time period. More practical plans about the technologies and strategic investment plans to the infrastructure should be introduced.

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