Zero-Carbon Combined Transport

Technology and efficiency analysis of zero-carbon road-rail combined transport

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INTERNATIONAL UNION FOR ROAD-RAIL COMBINED TRANSPORT

Contents

Acknowledgments

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Management Summary

The transport sector currently contributes almost 30 % of the EU's annual greenhouse gas emissions due to the high share of freight transported by road. Consequentially, a quick and significant reduction of emissions from transport is necessary to meet the European climate targets. Door-to-door road-rail combined transport already transports goods at a fraction of the CO_2 emissions (60 % – 90 % less) accompanied by a pro-rata energy efficiency increase of 40 % – 70 % compared to long-haul trucking. This is mainly due to the advantage regarding energy efficiency of railway over transportation by diesel-powered trucks. Moreover, even zero-carbon door-to-door combined transport is feasible with the technology available already in the market today.

Zero-carbon combined transport is enabled by electrification of transport for the involved modes as foreseen in the IPCC Sixth Assessment Report. With today's battery technology, electric trucks are suited for combined transport, as the typical road leg distance is short – usually below 70 km. The transhipment equipment for intermodal terminals can also be substituted by electric alternatives available in the market. There are no market-ready battery-electric shunting locomotives yet, but the necessary technologies are already available today, hence the electrification of shunting can be considered a matter of time. Regarding costs, battery prices are projected to decrease in the future, and prices for vehicles and equipment are expected to decrease due to a ramp-up of serial production.

With the widespread electrification of railway main lines, rail freight transport is locally emission-free as standard and progresses towards zero-carbon through commitments by railway undertakings to use renewable electricity. In order to use the limited supply of green electricity efficiently, further measures and developments to improve energy efficiency are currently being implemented, e.g., by the usage of longer trains (740 m and longer) and digital automatic coupling. Consequently, the efficient bridging of modes by the intermodal technique enables the shift towards energy efficient freight transport and the rapid and efficient reduction of greenhouse gas emissions. In contrast, limited scale efficiency improvements can be reached within the modal silos.

As zero-carbon combined transport is already feasible today from a technical as well as operational perspective, different measures are needed to fully use its potential for achieving the EU’s climate targets. On the one hand the share of combined transport of total freight transport must be increased, on the other hand the necessary steps to develop a wide-spread network of complete zero-carbon transport relations from the few options in the market today needs to be taken.

Introduction

The 2021 IPCC report states that the atmospheric CO_2 concentration in 2019 was higher than at any time on earth during the last 2 million years. In order to limit the increase in global temperature to 1.5 °C, the CO_2 concentration has to peak before 2025. The increase of the global surface temperature since 1970 is faster than in any other 50-year period over at least the last 2000 years and severe weather conditions become more frequent and more intense [1, 2]. Hence, climate change can be considered as a threat to Europe and the world.

In the light of this development, the importance of reducing greenhouse gas (GHG) emissions across all sectors becomes evident. While the average decline in the EU's domestic GHG emissions between 2005 and 2020 across all sectors was 2.67 % p.a., the transport sector could not compete with this, as its average decline in GHG emissions counts 1.64 % p.a., which is the lowest compared to all other sectors (Figure 1). As a result, the transport sector's share of the overall GHG emissions in the EU increased from 14.8 % to 28.3 % in the last two decades [3]. In order to meet the European objective of climate neutrality by 2050 set out in the European Green Deal [4] and laid down in Article 2 of the European Climate Law [5], ambitious reduction targets will have to be set for the sector.

In the 2011 EU Whitepaper[1], ten goals for a competitive and resource efficient transport system were set for achieving the 60 % emission reduction target by 2050[2]. One of these goals was to shift 30 % of the road transport over 300 km to other modes by 2030, and more than 50 % by 2050. In contrary to the expectations at that time, the share of road transport has even slightly increased from 74 % in 2011 to 76.4 % in 2019 [6]. This can be understood and explained by the fact that modal

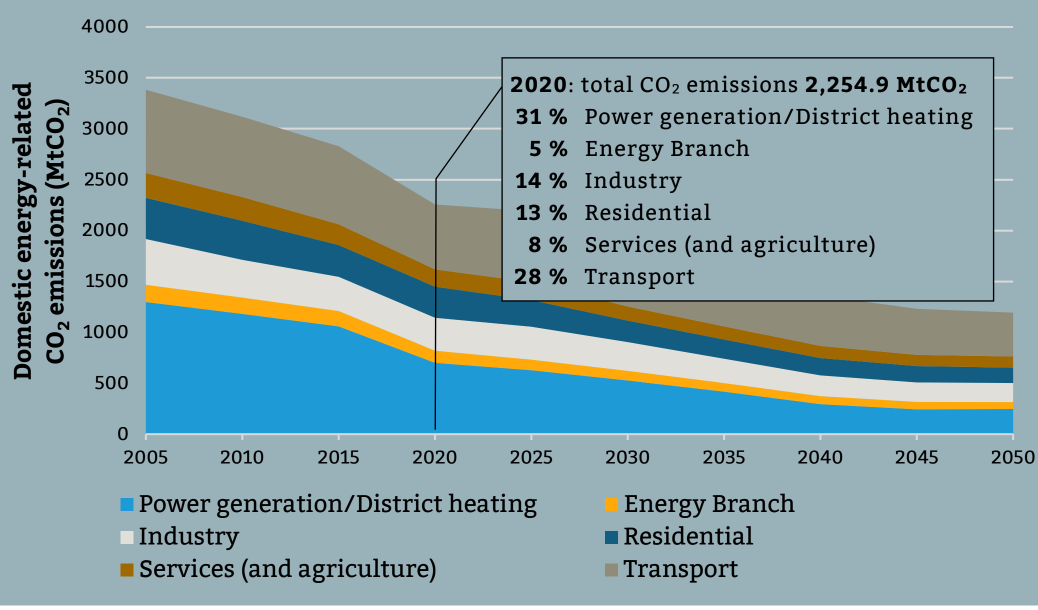

Figure 1: Domestic energy-related CO_2 emissions by sector according to EU Reference Scenario [3].

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[1] EU Whitepaper Com(2011) 144 "Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system".
[2] This reduction target was set in 2011. The commission announced a new target to limit the rise in global temperature to 1.5 °C in its proposal COM(2020) 562, in which a GHG reduction target of 55 % by 2030 compared to the level of 1990 is set.

shift was introduced as a KPI without associated policy measures, so the focus was primarily on optimising the efficiency of road transport itself to achieve the emission reduction target. While Switzerland invested 60 % of federal infrastructure budget in railway infrastructure, Germany on the other hand only invested 47 % in rail and the remainder in the road infrastructure in the year 2016 [7].

As road transport is a main driver for the transportation sector's emissions [3] a shift towards a more energy efficient and lower-emission mode of transport can lead to a more significant emission reduction [8] than the continued optimisation of road transport. A recent study showed that rail-road door-to-door combined transport (CT) allows for emission reductions of 60 %–90 % compared to road transport, while offering a 40 %–70 % pro-rata energy efficiency improvement [9]. Door-to-door CT offers a close alternative to long-haul trucking, as it is more labour- and energy-efficient.

The technology needed for zero-carbon CT is basically available and in use today, which make it a good option to deliver the carbon-neutrality in overland cargo transport. No significant scientific breakthroughs are required to enable zero-carbon freight transport. The key factors are zero-carbon electricity generation [10], electrification of rail, the use of electric equipment for transhipments [11] and short distance regional battery electric vehicles for road legs [12].

In this study we examine the technology perspective of sustainable transport, indicate the costs and investments needed for zero-carbon CT and compare the energy efficiency of CT to long-haul trucking while considering and assessing the potential of modern technologies.

1. The technology perspective on sustainable transportation

In order to achieve zero-carbon transport, it is important to promote the use of propulsion technologies that enable the use of zero-carbon fuels and energy sources while focusing on the greatest energy efficiency achievable. In this chapter, the energy efficiency of different transportation modes and propulsion technologies are compared. In the course of this, the energy efficiency as well as the greenhouse gas (GHG) emissions in CO_2 equivalents well-to-wheel are estimated in order to understand which propulsion technologies already enable zero-carbon transport and are efficient at the same time. Battery electric vehicles have particular potential for the use on road legs in CT, therefore different battery technologies are compared by cell voltage and energy density, followed by an outlook on the EU's path for decarbonised electricity generation.

1.1 Energy efficiency of transportation modes

To firstly assess and secondly to reduce the CO_2 emissions caused by (freight) transport, it is worth looking at the **energy efficiency of transport modes**, as promotion of energy efficiency also forms part of the "Fit for 55"-package with the view of reducing net GHG emissions. Moreover, energy efficiency has become an important consideration with the need to reduce Europe's dependency on external energy supplies. The following section provides a comparison of energy efficiency including an analysis of its drivers and obstacles for rail and road transport – the modes of CT, which are also dominant within freight transport in the EU (rail 17.6 % and short- and long-distance road 76.3 % [13].

Regarding **rolling friction**, steel train wheels on rail have a power of ten lower rolling friction coefficient compared to rubber truck wheels on asphalt. Thus, less kinetic energy is dissipated to thermal energy resulting in higher energy efficiency while fewer fine particles (PM 2.5) are released. Hence, from a tribology perspective rail transport is more efficient compared to road transport [14].

In addition, energy efficiency is significantly influenced by **aerodynamic drag**, which increases proportionally to the square of the speed. Thus, aerodynamic aspects influence the design of trucks [15] and trains [16] and further techniques to improve aerodynamics are increasingly being developed and piloted. For example, platooning of trucks reduces aerodynamic drag by using the slipstream of the vehicle in front. Such techniques are fostered by technological developments like in this case cooperative adaptive cruise control to allow several vehicles to follow each other in a certain distance and at steady speed [17, 18]. In the case of (freight) trains, this technique is already utilised by design. By combining up to 35 wagons in one train up to a length of 740 m [19], the slipstream of the whole chain can be utilised, whereas a truck platoon usually comprises three to five vehicles [20]. Further details on aerodynamic improvements and the impact of the velocity on their effectiveness can be found in Section 3.2 of the study.

There are other aspects that can influence the transport mode's energy efficiency such as the **route's topology**, as changes of the rail or road's vertical and horizontal gradient cause losses in energy efficiency [21, 22]. Since railway tracks are more limited concerning gradients compared to roads, they are – from a topological point of view – preferable for more efficient transport services.

Besides the energy efficiency aspect, there is also a social component when comparing long-haul trucking to CT. Low salaries, social stress from being away from home for prolonged periods, the strain stemming from the dynamically increasing complexity of scope of work, and a shifted age structure are factors contributing to the shortage of long-haul truck drivers in Europe [23]. Typically, the road leg distance in CT is below 70 km[3] [24]. Hence, truck drivers within CT do not have to spend the nights away from home which can reduce social stress on the drivers and improve the work life balance, while potentially also facilitating a longer-term retention of drivers.

1.2 Propulsion technologies for heavy-duty vehicles

Well-to-wheel (WtW) analyses take the fuel's production, processing, transport, and consumption into account whereas **tank-to-wheel (TtW)** analyses only consider consumption and **well-to-tank (WtT)** analyses comprise the fuel's production, transport, and processing.

Today in 2022, heavy duty vehicles are still mainly powered by fossil fuels – primarily diesel. Since combustion is a main contributor to worldwide CO_2 emissions, other, more sustainable propulsion technologies (e.g., battery- or fuel-cell electric drive) receive more attention. While the substitution of conventional drives with more sustainable alternatives is essential to enable zero-carbon transport, the energy efficiency of these technologies is an important and highly relevant criterion for their assessment. In this section, different propulsion technologies are explained and compared by their GHG emissions and energy efficiency well-to-tank, tank-to-wheel, and well-to-wheel (see info box for further explanation).

Battery electric vehicles (BEV) are using an electric motor to convert electric energy into kinetic energy, which is provided by large capacity rechargeable batteries stored on-board. In the following, a distinction is made whether the charging electricity comes from renewable sources (green BEV) or from the EU's electricity mix (BEV). For the green and conventional BEV, there is no difference in terms of the propulsion technology itself, but the source of electricity generation influences the GHG emissions significantly. Therefore, the CO_2 footprint of a BEV, like its fuel-cell electric brethren's described below, depends on the source of power.

Fuel cell electric vehicles (FCEV) are powered by converting the chemical energy of hydrogen and oxygen released in electrochemical oxidation that takes place in a fuel cell, into electric energy which serves as energy source for an electric motor. In FCEV vehicles a small battery and a fuel cell plus hydrogen tanks replace the large batteries in BEVs. The hydrogen fuel can be obtained in different ways. Since the focus of this study is on low-emission transport, green and blue hydrogen are considered. Green hydrogen is produced by the electrolysis of water using electricity from renewable sources. To produce blue hydrogen, steam methane reforming (SMR) or auto thermal reforming (ATR) are being used to separate natural gas into hydrogen and carbon dioxide. Instead of emitting the resultant CO_2, it undergoes the process of carbon capture, utilisation, and storage (CCUS) to separate it from hydro-

[3] In unaccompanied CT the road legs are estimated to equate to 10-15 % of the rail leg which is 850 km for international CT within the EU. Regarding UIRR members, 80 % of their services are unaccompanied CT.

gen [25], capture it and store it, e.g., within suitable geological formations[4]. Carbon capture is capable of trapping 65 % of the CO_2 by-product of blue hydrogen production. Apart from the uncaptured CO_2, fugitive methane during the H_2 generation process leads to additional GHG emissions. For the estimation of the blued hydrogen's GHG emissions a methane leakage rate of 3.5 % is considered [25]. Due to the small molecular size of hydrogen, fugitive hydrogen caused by leakage through casing and pipework or venting during the fuel cell's start-up and shutdown is not uncommon. This can be an issue as released hydrogen reduces the atmospheric hydroxyl radicals and therefore, increase the lifetime of methane as it cannot react to CH_3 and H_2 [26, 27]. Volatile hydrogen can also emerge from transport processes, although progress has already been made in this area in the use of metal hydrides, such as the so-called Powerpaste [28], which uses magnesium as a storage medium. However, the production process is very energy-intensive, as it requires high process temperatures and pressures.

Trolley-truck or catenary electric vehicles can be equipped either with an additional diesel engine or with a small battery, which usually only allows ranges of approximately 10 – 15 km [29]. Trolley trucks are severely limited in their flexibility and routing due to their infrastructure dependency – away from roads with overhead lines, they need to drive as a normal BEV or diesel truck with the additional weight and aerodynamic drag of the pantograph equipment. In addition, overhead lines would cause additional construction and maintenance costs (see Section 2.3) and might cause additional safety risks. Therefore, trolley trucks are not a viable nor cost-effective alternative for reducing GHG emission.

From a **WtT** perspective, battery-powered electric vehicles are more efficient compared to hydrogen-based propulsion technologies, as fewer energy conversion processes such as electrolysis or SMR/ATR with CCUS are required, which reduce efficiency. Especially CCUS significantly reduces the energy efficiency of blue hydrogen as it requires 5 - 11 MJ of energy per kilogram of CO_2 [30]. As a result, the efficiency of hydrogen production is nearly as low as the efficiency of diesel production (approximately 30 % for both) [30, 31, 32, 33]. However, there is a significant difference in emissions. While the upstream emissions of green hydrogen from compression and distribution are lower compared to the

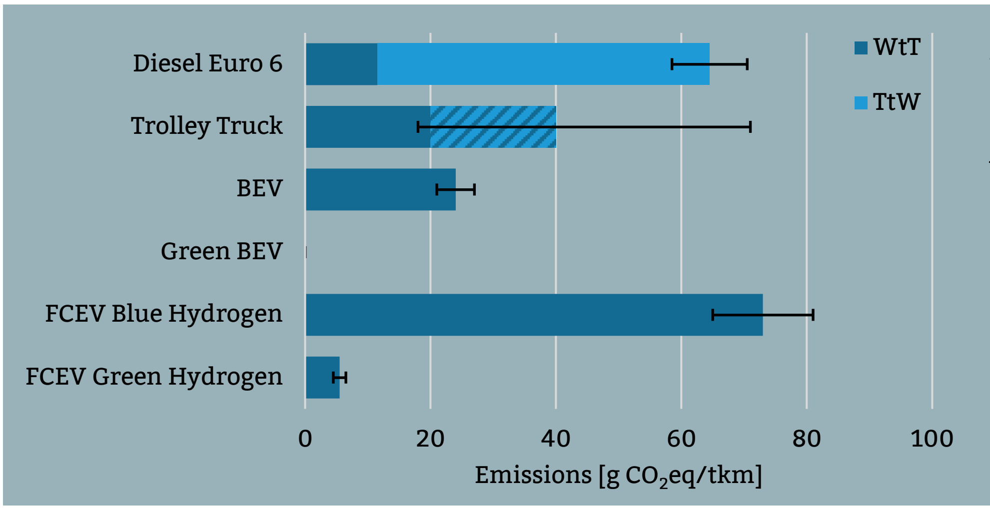

Figure 2: WtT and TtW emissions per tonne-kilometre for different propulsion technologies. WtW emissions are indicated as the sum of WtT and TtW emissions. Data shown in Table 1. For trolley trucks, emissions in combined operation (catenary and off-catenary) are considered.

[4] Geologic sequestration of CO_2 involves risks like triggering earthquakes or CO_2 leaks. However, these risks must be weighed against the risk of further emitting CO_2 [102].

Table 1: Overview for energy efficiency and GHG emissions for different propulsion technologies for heavy-duty vehicles WtT, TtW, and WtW per tonne-kilometre. The energy efficiency in this table is defined as the energy needed to transport one tonne for one kilometre. The higher the numerical value for a corresponding propulsion technology, the less efficient it is since more energy is needed to transport one tonne for one kilometre [25, 34, 35, 36][7].

		FCEV Green Hydrogen	FCEV Blue Hydrogen	Green BEV[5]	BEV	Trolley-Truck[6]	Euro6 diesel
Energy Efficiency [MJ/tkm]	**TtW**	0.4 – 0.58	0.4 – 0.58	0.33 – 0.42	0.33 – 0.42	0.29 – 0.73[6]	0.66 – 0.73
GHG Emission [g CO_2eq/tkm]	**WtT**	5 – 6	65 – 81	0	21 – 27	18 – 27[6]	9 – 14
	TtW	0	0	0	0	0 – 56[6]	50 – 56
	WtW	5 – 6	65 – 81	0	21 – 27	18 – 69[6]	59 – 69

WtT emissions of diesel, blue hydrogen has very high WtT emissions due to fugitive methane emissions during the SMR process (see Figure 2). Moreover, not all CO_2 generated by the SMR process can be captured. Different reviews state carbon capture rates of approximately 65 % [25]. This brings blue hydrogen and diesel to a similar WtW emission level.

From a **TtW** efficiency point of view, fossil fuel-based propulsion technologies can only reach a maximum efficiency of 60 %, as this is the Carnot cycle's efficiency an ideal thermodynamics cycle. At the moment, the newest generation of Euro 6 diesel trucks can reach efficiencies up to 50 % [37]. The same level of efficiency can be observed for FCEV, as the electrolysis on board the vehicle alone reduces the efficiency by 40 % [35]. The efficiency losses from BEVs are mainly due to charging losses and ohmic losses from the electric motor that causes an energy efficiency reduction of 12 – 14 %[8]. Since trolley trucks are using the catenary to power their electric motor, charging losses are relevant for the off-catenary driving mode. As a hybrid vehicle, the emissions in combustion engine operation are as high or even higher than for diesel Euro 6 vehicles, as the equipment and higher air resistance result in lower energy efficiency. Looking at local emissions, only the conventional diesel truck emits CO_2 directly, the electric and hydrogen-based propulsion technologies do not produce any emissions when driving.

As a result, the BEV is the most efficient vehicle in a **WtW perspective** and the most flexible vehicle for transporting goods in the last mile. Compared to hydrogen-powered vehicles, fewer process steps are required from power generation to propulsion and they are less complex vehicles. From an emission point of view, green hydrogen powered FCEVs have the potential to be zero-carbon, given the hydrogen compression and distribution is also powered by renewable energy sources.

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[5] For the green BEV, the need electricity comes from renewable wind energy.
[6] Energy efficiency and emissions of trolley trucks depend on the mode of operation, i.e., either catenary or battery/ diesel range extender. In off-catenary mode, the emissions and efficiency of a normal BEV or diesel truck are assumed, respectively. Actual values can be higher due to the additional weight and aerodynamic drag of the pantograph equipment.
[7] For the WtT emissions of blue hydrogen, a methane leakage of 3.5 % was assumed [25], which was not considered in the JEC Well to Tank report v5 [36]. The emission intensity of power generation was updated based on EEA values for the EU-27 electricity mix for 2020 [34] and used for the calculation of WtT emissions of BEV and trolley-truck.
[8] Fast charging can further reduce the energy efficiency

However, green hydrogen powered FCEV do not reach the energy efficiency of BEVs (see *Table 1*). FCEVs powered by blue hydrogen are not a sustainable alternative to conventional fossil fuel-based propulsion technologies from an emissions and efficiency perspective as long as fugitive methane is released into the atmosphere and the energy-intensive CCUS process is required. Presently, BEV are the most promising technology due to their high efficiency and low GHG emissions (see Table 2). However, the range of today's batteries for heavy-duty battery electric vehicles is limited to approximately 300 km [38]. This affects mainly long-haul trucking as single road legs in CT are typically below 70 km. Therefore, zero-carbon CT road legs in CT can be realised by today's BEV technology.

Table 2: Comparison of BEV (green) and FCEV (green hydrogen) by means of the fuel production, distribution, fuelling, conversion of fuel and R&D outlook [28, 39, 40, 41, 42, 43].

BEV (green)	FCEV (green hydrogen)
Fuel production	
Electricity generation by renewable energy sources	Electrolysis of water with electricity from renewable sources
+ *CO_2-emission-free process*	+ *CO_2-emission-free process*
- *Limited supply of green electricity (supply is expected to increase in the course of future development of production capacities)*	- *Losses due to energy conversion in electrolysis* - *Limited supply of green electricity (supply is expected to increase in the course of future development of production capacities)* - *Demand of fresh water for fuel production via electrolysis*
Storage	
Storage of green electricity by ▪ Battery ▪ Gravity battery (e.g., pump storage) ▪ Power-to-Gas/-to-Liquid ▪ Electric thermal energy storage ▪ Further methods that are currently piloted (Storage of green electricity becomes increasingly important to compensate for seasonal fluctuations in energy production as the share of renewable energy sources in the electricity mix increases)	Different storage options depending on the application. Basic distinction between ▪ Compressed gaseous hydrogen (up to 700 bar) ▪ Liquified hydrogen (cooling below - 235 °C needed for liquification) ▪ Chemical storage (e.g., metal hydrides, ammonia)
+ *Use of mature methods and existing technologies and facilities possible*	+ *Comparatively high energy density* + *Storage of hydrogen is possible without conversion to other energy carriers*
- *Energy carrier for storage necessary* - *Use of rare earth material for batteries required for currently dominant battery chemistry* - *Energy losses due to charging or conversion for batteries*	- *High energy demand for cooling or pressurisation for storage with high energy density* - *Material for chemical storage (e.g., ammonia) is often environmentally hazardous and requires additional safety procedures and precautions*

Fuel distribution	
Utilisation of the existing transmission and distribution grid infrastructure	Distribution of hydrogen in the according state or form of storage via ▪ Pipelines for compressed gaseous hydrogen ▪ Tanker vehicles and vessels for large distance transport of liquified of hydrogen ▪ Tanker vehicles and vessels for long-distance transport ▪ Tanker vehicles and vessels for long-distance transport chemical carriers (such as ammonia or methanol)
+ *The existing infrastructure is to a large extend appropriate and functional*	+ *In subareas and through admixture, the existing natural gas distribution infrastructure can be used for gaseous hydrogen*
- *Voltage peaks can emerge in the grid due to charging processes* - *The installation of additional transmission capacities may become necessary*	- *For widespread availability, substantial installation of infrastructure for distribution is required (e.g., pipelines made of steel with high resistance to hydrogen embrittlement, cyrotanks, terminals)* - *Environmental hazards due to chemical carriers such as ammonia* - *Energy demand associated with distribution*
Fuelling	
Fuelling by charging the battery with alternating (up to 22 kW) or direct current (up to 50 kW)	Typically, pressure fuelling (up to 700 bar). Concepts for refuelling by cartridge with metal hydride (e.g., MgH_2) are under development
+ *Installation of charging stations is possible without significant expense (as long as not limited by grid load)*	+ *Short fuelling time due to pressurised fuelling*
- *Comparatively long charging time (for existing battery types and efficient charging currents)* - *Energy losses due to the battery's internal resistance*	- *Fugitive hydrogen during the fuelling process*
Conversion of fuel	
Electrical energy usable without further conversion	Electricity is generated by the conversion of hydrogen and oxygen in the fuel cell
+ *No losses of energy due to conversion processes* + *CO_2-emission-free process*	+ *Longer ranges possible due to comparatively high energy density* + *CO_2-emission-free process*
	- *Energy losses due to the conversion process in the fuel cell*
R&D outlook	
Current research focuses include the enhancement of energy density of batteries and battery production from more environmentally friendly materials (see Section 1.3).	Research focuses include among others the development of more efficient and higher energy density storage and distribution solutions as well as the development of non-hazardous carrier materials.

1.3 The development of battery technologies

Battery electric vehicles are a propitious technology to enable zero-carbon transport. The batteries are necessary to provide the electric energy and are also used for recapturing and storing of braking energy. At the moment, lithium-ion batteries are the preferred choice by today's vehicle manufacturers according to their relatively good energy density [44]. However, the global lithium resources might not be able to sustain simultaneous mass electrification of heavy-duty and light-duty vehicles [45]. Thus, alternative materials for batteries such as sodium and iron are subject of scientific research and under commercial development. In Table 3, different battery technologies are being compared by their nominal cell voltage, energy density by mass and volume, price, and the battery's estimated mass and volume for a 400 km distance long-haul trucking scenario (a battery capacity of 600 kWh is assumed for this scenario)[9].

Regarding this scenario, lithium cobalt-based batteries are momentarily the only suitable option for such a distance considering their high energy density. However, sodium-ion batteries could become a viable substitute for lithium-based batteries in the future, as sodium is abundant, and its price is lower compared to lithium [46]. An example for a project focusing on the development and testing of natrium-ion batteries is the EU funded NAIMA project [47]. Broad research is also carried out on iron-air battery cells, as these materials are also abundant and less expensive. However, conventional iron air batteries have an energy efficiency of less than 50 % [48] which is lower than the energy efficiency of lithium-based batteries [49]. Furthermore, solid-state batteries are of great interest because of their wide range of operating temperature, their inherent higher safety due to the absent of flammable liquid components, as well as their energy density, and the possibility of fast charging. With a prototype, energy densities of up to 450 Wh/kg [50] could be achieved. Automobile manufacturers estimate that solid states batteries are market ready earliest by 2025 [51].

Table 3: Overview on modern battery technologies [52, 53, 54, 55, 56].

Dimensions	LiCoO2	LiMn2O4	Na^+	Na-NiCl2	Fe-Air*
Nominal Cell Voltage [V]	3.6	3.7	2 – 3.6	2.58 – 2.8	1.28
Energy density by mass [Wh/kg]	150 – 200	100 – 150	160	100 – 120	50 – 110
Energy density by volume [Wh/litre]	220 – 350	270	NA	165	NA
Battery Price [EUR/kWh]	125 – 275	275	65	550-750	<90
400 km distance scenario					
Stored Energy [kWh]	600	600	600	600	600
Mass [kg]	2,320 – 3,093	3,093 – 4,640	2,900	3,867 – 4,640	4,218 – 9,280
Volume [litre]	1,226 – 2,109	1,718	NA	2,812 – 1,750	NA

[9] An energy consumption of 1.4 kWh/km is assumed [106]. 400 km cover 50 % of the road freight transport activities in Germany [104].

Despite developments towards an improvement in energy density, it is questionable if BEVs will become suitable for long-haul trucking, as longer distances require stopovers for recharging or larger batteries causing a reduction of payload due to the batteries' weight. In comparison, single road legs in CT are typically shorter than 70 km[10]. To allow for this distance, a reduction of battery weight of approximately 80 %[11] compared to the 400 km scenario would be possible. Hence, with today's battery technology full electric transport on road-legs is feasible and possible. Moreover, electrification by the use of batteries is also a viable and already operational technology to power modern terminal tractors and reach stackers [57, 58].

However, fully electric road transport is one intermodal leg in CT. To enable zero-carbon CT in total, decarbonisation of electricity generation is also necessary to enable zero-carbon rail transport and zero-carbon transhipment.

1.4 Decarbonization paths for electricity generation

Recent strategic decisions such as the *Joint European Action for more affordable, secure and sustainable energy* (RePowerEU, [101]), with the objective of becoming independent of gas imports sooner, will also have an impact on the power mix.

Due to specifics such as the typical leg lengths, CT has the opportunity to combine the existing potential of rail transport with energy-efficient electric trucks and electrified transhipment technology. For these electrically powered means of transport, the emissions directly depend on the emission intensity of power generation. Thus, the use of electricity from renewable sources facilitates zero-carbon transport.

Regarding emissions reduction and the use of renewable energy sources, Europe has set itself ambitious climate targets in the Green Deal [4]. With the European Climate Law [5] and amending policy packages like the "Fit for 55" [59], the legislative basis has been set to deliver on the climate targets – a 55 % reduction of GHG emissions by 2030 compared to 1990 and climate neutrality by 2050.

In support of the legislative process, reference scenarios modelling the long-term evolution of economy, energy, transport, and emissions based on the policy framework in place are regularly calculated. The current EU Reference Scenario 2020 [3] is calibrated based on EUROSTAT data up to 2020 and projects the different indicators in steps of five years up to 2050. Based on this, different policy scenarios were calculated as part of the impact assessment of the "Fit for 55" package.

These scenarios will be used to provide an outlook on the decarbonisation of electricity generation until 2050. Figure 3 shows the development of the shares of different energy sources for electricity generation for the period from 2005 to 2050. In the updated, "Fit for 55"-compatible scenario, zero-carbon energy sources (renewable and nuclear) reach a contribution of 81 % to electricity generation by 2030, while this rises to 86 % by 2050 in the reference scenario.

This development also has an impact on the emission intensity of electricity generation. The European Environment Agency publishes statistics on GHG emission intensity for the period from 1990 up to today, as well as trajectories for the development until 2030 according to the "Fit for 55"-compatible policy scenarios [34] (see Figure 4). The projection shows that the ambitious emission targets can be met if the current

[10] The ongoing terminal development programmes in Europe, promise a further reduction in CT road leg distance [105].
[11] For estimating the weight reduction, a linear correlation between distance and energy consumption was assumed.

trend were to continue. With its comparatively high pro-rata energy efficiency (40–70 % better than unimodal road haulage powered by a Euro 6 diesel powertrain), the utilisation of electricity from renewable sources in door-to-door CT enables its efficient use.

In conclusion, emissions in CT can be reduced at the rate at which electricity generation in Europe is becoming climate neutral. For the coming years, a continuous reduction in emissions can be expected due to the development of energy generation, without having to rely on technical improvements and innovations for vehicles, propulsion technology and infrastructure.

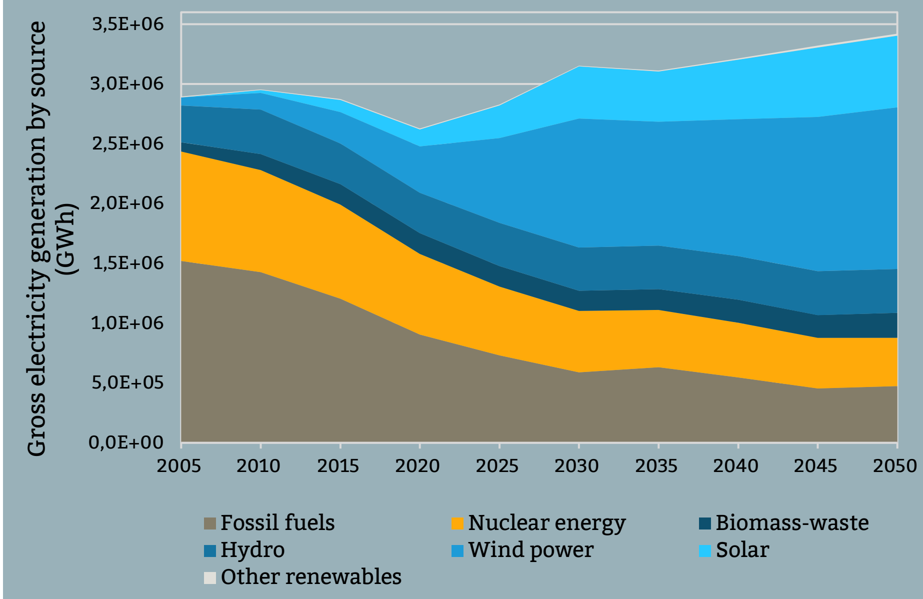

Figure 3: Gross energy generation by source (GWh) for different renewable energy sources as well as nuclear and fossil sources. Data up to 2030 taken from the "Fit for 55" MIX scenario [59] (data from 2005 to 2020 from EUROSTAT) and for 2035 to 2050 from the EU reference scenario 2020 [3].

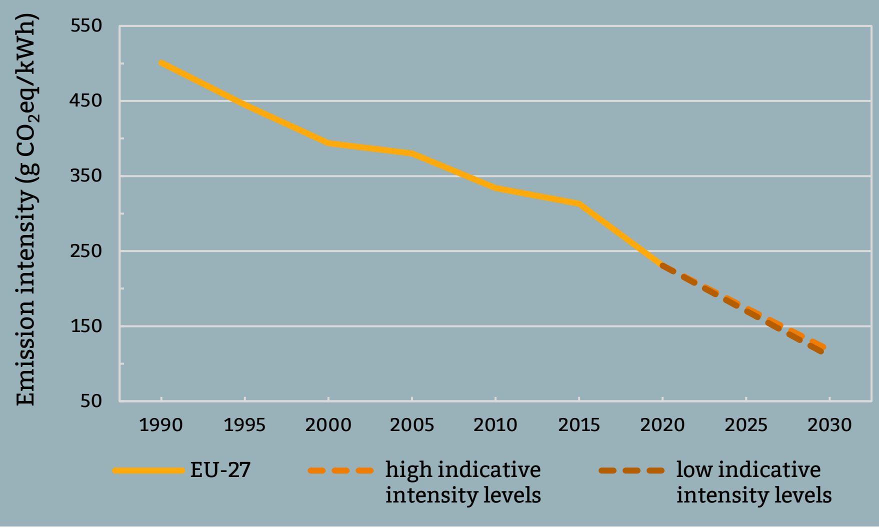

Figure 4: GHG emission intensity of electricity generation on European level. 2020-2030 trajectories represent "Fit for 55"-compliant intensity levels. Data from EEA [34].

2. Costs and investment needs for zero-carbon combined transport

In order to enable zero-carbon CT, the technology to allow for electrification and foster energy efficiency is not the only necessity. Financing of the measures must be feasible without entailing additional investment needs, which would make a realisation unprofitable.

2.1 Electrification of terminal equipment

With the EU's 2021 Connecting Europe Facility (CEF) call for proposals, a funding program was launched for devolving – inter alia – rail-road terminals on the Trans-European Transport Network (TEN-T) with a total amount of €350 million. Eligible is the construction or modernisation of terminals to comply with the requirements of the TEN-T regulation, e.g., power connections, safe and secure truck waiting areas, adaptations for 740 m train length, clean transhipment equipment for intermodal loading units (ILU), semi-trailers and tractor-trailer combinations (rolling motorway) as well as information and communication technology (ICT) equipment and applications [60]. In the following, the investment required for clean transhipment equipment as an enabler for zero-carbon CT is evaluated. The €350 million – considering the 30 % average funding ratio – should trigger investment worth well above of €1 billion.

Typical transhipment equipment comprises terminal tractors, reach stackers as well as rubber tyred (RTG) and rail mounted gantry cranes (RMG). Except for RMGs which are typically electric, this equipment is usually powered by diesel engines and therefore emits GHGs besides also causing noise and impacting the air quality at the terminals. In the following, the electrification potential and the purchase price of different transhipment equipment is assessed.

Figure 5: Terminal tractor ("Sisu terminal tractor at Katajanokka Quay in Helsinki" by Anttii Leppänen, CC BY 4.0)

Terminal tractors are intended to move semi-trailers within a cargo yard like an intermodal terminal – consequently they are used both in terminals build for horizontal transhipment techniques and in terminals using vertical handling facilities for the transport of non-craneable and craneable semi-trailers, respectively. As of today, several manufacturers offer electric powered terminal tractors. These are equipped with battery packs with a capacity of up to 182 kWh, which results in an operating time of up to 12 hours at an average energy consumption of 15 kWh/h [61]. The TtW GHG savings in comparison to a conventional diesel-powered tractor is 25.45 kg of CO_2eq per hour and per tractor [62, 63]. Based on the consultation and interviews with industry experts at manufacturers and operators, the current purchase price for one electric terminal tractor can range between €260,000 and €377,000. Infrastructure investments for construction of an adequate charging station are in the range of €20,000 to €25,000. Since terminal operation is not continuous, charging can be scheduled during periods of low terminal utilisation without requiring additional equipment for securing handling capacity when using electric equipment.

As well as terminal tractors, **reach stackers** can be found in vertical and horizontal handling facilities as they are used for the transport and staging of craneable ILUs within the terminal. Currently available electric reach stackers are equipped with a battery capacity up to approximately 590 kWh, resulting in a feasible operation time between 7.5 and

Figure 6: Reach stacker ("Kalmar Peinemann reachstacker" by Joost J. Bakker, CC BY 2.0)

10 h. The maximum load for the electric reach stacker, like for its fossil fuel counterpart, amounts to 45 t. The additional weight of the electric battery can be utilised to substitute the counterweight that conventional reach stackers require for stabilisation during lifting processes. In the TtW perspective, switching to an electric reach stacker can save up between 25 and 37 $kgCO_2eq$ per hour depending on capacity utilisation [64, 62]. Prices for fully electric reach stackers could not be determined, as these will first be delivered in Q4 2022, but hybrid reach stacker on the market can be used for orientation – with prices ranging between € 700,000 and € 800,000. Due to the larger battery, it can be assumed that the purchase price for a fully electric reach stacker is higher than for its hybrid brethren's. Like for terminal tractors, transhipment processes using electric reach stackers do not require significant adjustments or additional equipment compared to conventional reach stackers since charging can be scheduled during periods of low terminal utilisation.

Figure 7: Rubber tyred gantry crane ("RTG aka Rubber tyred gantry crane by Konecranes in Finnish factory at Hyvinkää test site" by Derek Yu, CC BY 2.0)

Rubber tyred gantry cranes are mobile equipment used in vertical terminals for handling of ILUs. Conventional RTGs are powered by diesel generator of approximately 410 kW with a fuel consumption of about 14 l/h which results in 31 $kgCO_2eq$ per hour of GHG emissions considering the TtW perspective [65, 62]. In comparison, an electric RTG does not emit any emissions at the source and allows for higher efficiency as fuel does not need to be converted into electricity. Typically, electric RTGs are primarily powered via a busbar or cable reel power system, while the battery is used for cross-stack travel and maintenance operation. As a measure for enhancing energy efficiency, regenerative energy is used for recharging the battery when setting down ILUs. Since the diesel engine usually only serves as a generator for electricity, existing diesel-powered RTGs can be fully electrified by retrofitting a cable reel. Due to very individual preconditions regarding the terminal's size and power grid as well as pre-existing RTGs at the terminal, an indication of price is not expedient.

Horizontal transhipment techniques such as CargoBeamer, Modalohr, or Rolling Highway (RoLa) are electrically powered already today. A **CargoBeamer** system handles trailers in a horizontal loading and unloading zone. The investment costs for a system for handling of up to 260 loading units per traffic day are approximately € 24.5 million. The **Modalohr** system allows horizontal transhipment using a low-floor double carriage with a turnable upper structure. The truck can be driven onto the wagon by folding out the special equipped wagons. The investment needed for the Modalohr system are approximately € 19 million again for handling of up to 260 loading units per traffic day. **RoLa** is a railway system that allows trucks to drive horizontally onto the railway rack in a row. Installation costs for a loading ramp are approximately € 100,000. For this technique, suited RoLa wagons are required that are higher in maintenance costs [66].

Shunting locomotives are not necessarily operated by terminals, yet shunting is an essential process step at many transhipment terminals. There are electric shunting alternatives on the market with installations, e.g., in ports, industrial plants, and rolling stock depots. However, these are limited regarding the maximum towing capacity [67]. In 2024, the first battery-electric shunting locomotive will be used in a major European port [68]. An installation that requires a movable, rail-mounted electrification system is currently piloted in Great Britain with the aim of replacing diesel shunting within a freight terminal [69].

Figure 8: TEN-T network corridors compliance map for electrification of railways. Tracks compliant with guidelines on electrification (i.e., electrified lines) are shown in blue, non-compliant lines in red, lines with no compliance data are black. Further lines of the core (green) and comprehensive (purple) network for which no KPI compliance assessment is performed, are included (Retrieved from the TENtec Interactive Map Viewer on 03/24/2022).

In conclusion, clean transhipment alternatives already exist today. Terminals can act as an enabler for seamless zero-carbon CT by providing charging infrastructure for BEVs operating on the first and last leg[12]. Using the time of a typical terminal visit of 30 to 60 minutes, recharging can be efficiently integrated into the operating schedule, increasing the range and operation time of BEVs.

2.2 Electrification of rail infrastructure

With the Union Guidelines for the development of the Trans-European Transport Network (TEN-T, [70]), the European Commission aims to enable efficient and sustainable transport by combining transport infrastructure development and policy aspects within this regulation. Considering railway infrastructure, full electrification of the line tracks is laid out as one of the requirements for the core network until 2030 and the comprehensive network until 2050. As the recent progress report [71] as well as the KPI compliance map provided by TENtec (see Figure 8) show, this requirement was already met in the core network for a large extent of 89 % per 2017 data, while it should be noted that not all non-electrified lines are used by freight trains.

The overall costs for reaching full compliance with the TEN-T guidelines have been assessed within the process of the revision of the TEN-T regulation[13] [72]. According to this analysis, reaching compliance with the unrevised TEN-T guidelines (EU REG 1315/2013) in the core network by 2030 requires an investment of €500 billion and an additional investment of €1,000 billion for the comprehensive network and compliance

[12] Potential safety hazards can be minimized by using contactless charging [103].
[13] The evolving political and economic context – especially the goals set out by the European Green Deal – necessitated the revision of the TEN-T regulation, to further provide the regulatory and strategic basis to stimulate low- and zero-emission transport by the build-up of adequate infrastructure. Since electrification of rail was already laid out in the 2013 TEN-T guidelines, these projects do not account for additional costs assessed in the quantitative analysis for a revised TEN-T policy.

by 2050. However, these estimates are for all modes of transport in total and they extend to full compliance with every TEN-T technical parameter, of which electrification is only one. The actual share of the TEN-T funding for rail projects of 56 %[14] can be used as an estimate for the investment need for the rail sector (passenger and freight). The €30 billion Connecting Europe Facility budget for the 2021-27 budget period should trigger investment of well over €100 billion. Annual investments into rail infrastructure development by Member States of the European Union amounted to €50 billion in 2018 [73].

Focussing on national infrastructure plans and programmes, the share of electrification projects in the total scope of construction projects (new and upgrade) becomes evident. Since the German 2030 Federal Transport Infrastructure Plan [74] provides a distinct cost estimate for electrification projects, these figures should serve as an example in the following. Of the total investment of €40.5 billion for prioritised railway infrastructure projects in the planning horizon from 2016 to 2030, 46% is planned for new construction and 54 % for infrastructure upgrades, which also includes electrification (€3.8 billion for a total of 934 km) that accounts for 9 % of the total investment. Using the investment sum per km derived from these values, the costs for electrification of the remaining 11% of the core network (total length approximately 63,000 km) can be extrapolated according to the methodology from [72] and would amount to a total of €28 billion. This corresponds to approximately 10% of the investment estimated above to achieve TEN-T compliance of the railway network. From this calculation it becomes obvious that electrification is already well advanced and that the necessary measures for expansion do not account significantly to the infrastructure investments.

On a sidenote, electrification of rail lines is not only an enabler for zero-carbon CT but goes in hand with further benefits. Electric traction allows for faster acceleration compared to diesel traction, thus permitting shorter operation cycles on the same track [75].

2.3 Electrification of trucks

As mentioned in Section 1.2, BEVs are a very suitable and promising technology for CT, considering the existing infrastructure, their high energy efficiency, and low emissions (with the direct potential to operate emission free when powered with green energy). However, as a consequence of electrifying transport on road legs, investments in new battery electric trucks have to be made. Looking at the total cost of ownership (TCO) for BEV and diesel trucks in major European countries, the BEV is expected to reach parity with the diesel truck latest by 2030 even without taking regulatory incentives such as purchase premiums, road toll reductions, and GHG emission premiums into account (see Table 4, [76]). Trolley trucks in contrast are not a viable nor feasible alternative, since they require the additional installation of catenaries. With €2.55 million up to €3.05 million [77] per kilometre the investment required for this technology is quite high.

[14] https://ec.europa.eu/inea/en/ten-t/ten-t-projects/statistics (accessed on 03/24/2022).

Table 4: Net present value (NPV) of the TCO per kilometre in Euro for a standard BEV and diesel truck for operation in long-haul trucking without considering regulatory incentives for selected European countries. Data taken from Figure 8 of [76][15].

		France	Germany	Italy	Netherlands	Poland	Spain	United Kingdom
2022	**BEV**	0.81	0.81	0.77	0.71	0.61	0.71	0.66
	Diesel	0.74	0.65	0.64	0.67	0.45	0.58	0.57
2030	**BEV**	0.60	0.59	0.58	0.48	0.45	0.52	0.45
	Diesel	0.70	0.62	0.60	0.62	0.48	0.58	0.52

For CT with typical single road legs below 70 km, the vehicle configuration of BEV and diesel trucks of the referenced study exceeds the requirements, and the battery size can principally be reduced by 70 % to still allow for the doubled road leg distance on a single charge. This affects the vehicle's weight, energy consumption, and acquisition price[16] and also has an impact on the loading capacity, as a smaller battery reduces the weight of the tractor and thus more payload can be carried[17].Another aspect of CT that reduces the price and weight of the truck is that a low equipped driver's cabin (regional configuration) is sufficient for the short distances around a base like an intermodal terminal, as it is not used for overnight stays, unlike the long-distance truck. According to industry experts and price lists of manufacturers, the price for a BEV in regional configuration is approximately 10 % lower compared to long-haul trucking configuration. Regarding weight, the smaller cabin allows for a reduction of the vehicle's weight of approximately 5 %, or 340 kg [78, 79].

Thus, the initial capital commitment for the acquisition of battery electric trucks suitable for CT is lower than for battery electric trucks used for unimodal road haulage. In the future, with more efficient and cheaper batteries becoming available, the required capital to invest in electric powered trucks will decrease even further. Forecasts estimate a reduction of 70% for the price of lithium batteries until 2050 compared to 2020 [80]. For a truck equipped with a 534 kWh battery[18], this would imply a purchase price reduction of approximately €72,000.

Furthermore, it can be assumed that the manufacturing of BEVs will also become more cost-efficient as assembly lines for electric vehicles are expanded and series production ramps-up. With regard to this, various manufacturers have set ambitious targets, e.g., to achieve a share of 50 % of all-electric trucks in overall production by 2030.

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[15] Assuming 500 km for 6 days a week for 52 weeks.

[16] Assuming 200 €/kWh the acquisition price is reduced by estimated €73,200.

[17] Due to the heavier propulsion technology, the battery electric truck's weight is compensated by two tones. However, according to a branch expert this does not fully compensate the additional weight for a long-haul battery electric truck and thus, results in up to 900 kg loss of payload.

[18] This is the capacity used by Volvos FH electric, which has a range 300 km range with a gross combination weight of 40 tonnes.

3. Technological developments beyond propulsion

An increase in energy efficiency and the use of efficiency measures are essential and necessary in order to achieve a net reduction in GHG emissions and to meet regulatory targets. In this context, a holistic perspective is appropriate, as there is also potential apart from propulsion technologies, discussed in Chapter 1. In the following, techniques and technologies currently being developed and tested are presented and assessed for both road and rail. The focus is on the concrete quantitative savings potential, advantages, technical requirements as well as obstacles and limitations.

3.1 The energy efficiency of rail freight transport

In this section, the focus is on two measures to improve the efficiency of rail freight transport – (1) the realisation of 740-metre-long trains in accordance with Article 39 of the Regulation (EU) No 1315/2013 and (2) efficiency improvements through the applications enabled by the digital automatic coupling (DAC).

For the core network, the TEN-T guidelines require a feasible standard **train length of 740 m** by 2030. However, the average freight train is shorter, e.g., in the case of Germany 64 % are shorter than 600 m [81], as the railway infrastructure presently does not allow the widespread circulation of 740-metre-long trains. Train length is a significant factor regarding energy efficiency: the use of a 740 m train instead of a 600 m train results in an efficiency gain of about 12 % per tonne-kilometre[19]. Therefore, using longer trains is an essential step towards more efficient rail freight transport and can at the same time help to reduce the capacity utilisation of the network.

In European countries, the current coupling standard for freight trains is the manual screw coupling (UIC standard). However, in the context of the ministerial conference "Innovative Rail Transport – connecting, sustainable, digital" in Berlin, the EU transport ministers have agreed on the introduction of the new **Digital Automatic Coupling** (DAC) by 2030 [82]**.** The system is able to couple wagons automatically making manual coupling and uncoupling of wagons no longer necessary. The essential value add is that DAC can automatically provide electricity and compressed air to every wagon of a train. Thus, DAC is an essential prerequisite to enable electronically controlled pneumatic braking of every wagon, which substantially improves the efficiency benefits of regenerative braking. Furthermore, the DAC system allows to supply reefer containers with grid power and, thus, to substitute clip-on diesel generators for reefer wagons. In the following, the efficiency gain enabled by these two use cases is assessed.

A **regenerative braking system** captures part of the energy that would typically be dissipated as heat during breaking and either stores it or feeds it back into the grid. With the use of such a system, an overall efficiency gain for the train operation of 10 % to 24 % can be achieved [83]. The efficiency can be further improved by the use of DAC

[19] For estimating the efficiency gain, the energy consumption of a 740 m and a 600 m freight train for the rail leg of transport relation No. 3 of "A comparative study on CO_2 emissions in door-to-door combined transport" [9] was compared. The calculation was performed based on EcoTransIT (accessed on 04/04/2022), with a parametrization according to the statistical scenario of the cited study, empty runs were neglected.

which allows the use of electronically controlled pneumatic brakes for the individual cars, enabling braking with maximum dynamic braking force. The result is an increase of the recuperation of energy per freight train by between approximately 3 % and 10 % [84].

Reefer containers need electricity to keep the necessary temperature for refrigerated transport. As of today, the standard energy supply for 40 (45) ft reefer containers is a 15 kW diesel generator [85], which require approximately 3.5 l of diesel to keep a container with 75 % of maximum load at the required temperature for an hour [86]. This results in an energy efficiency of 33 % and emissions of 9.6 kgCO_2eq per hour. Enabled by the application of DAC, it is possible to provide reefer containers with grid power, allowing to omit the inefficient process of electricity generation via the diesel generator. This way, GHG emissions for reefer consignments can be reduced significantly by up to 64 %[20] assuming the current emission intensity for power generation in the EU or even entirely if the electricity comes from renewable sources.

3.2 Impact on road freight transport‘s energy efficiency

Apart from propulsion, there is also potential for further efficiency improvements regarding road transport. In this section, (1) the impact on efficiency by operation of long trucks (25.25 m to 32 m) is assessed as well as (2) the effect of aerodynamic improvements regarding design or techniques such as platooning.

The reasoning and justification for the use of long trucks is the same as for long trains – namely to improve the efficiency per freight-tonne and distance. The efficiency gain from using **25.25-metre-long trucks** instead of truck with a length of 16.5 m can be quantified by 15 % [87]. This is due to the fact that in 80 % of the cases loading volume is the limiting factor instead of gross weight. Hence, a longer truck can carry loading units of larger volume or more loading units and, thus, more payload can be transported [88]. In Sweden, field tests with 32-metre-long trucks with a maximum permissible gross weight of 60 tonnes were carried out showing a potential for efficiency improvements of 27 %[21] compared to 16.5-metre-long trucks [89].

As mentioned in Section 1.1, efficiency can be improved by a **reduction of aerodynamic drag**. This can, e.g., be achieved through design elements, through platooning, and by reducing the vehicle’s maximum speed. **Design elements** such as side- and underbody panels with boat tail are improving the efficiency by 4 %[22] compared to a standard configurated Euro 6 diesel truck [90] without further aerodynamic design elements. Furthermore, techniques such as **platooning** (see Section 1.1) can improve the efficiency by 4.9 % to 8.6 %[23] depending on the vehicle’s position in the platoon, the speed of the platoon, and the behaviour of the preceding vehicles [91]. Therefore, it becomes obvious that for effective platooning a common platoon strategy and wireless vehicle-to-vehicle (V2V) communication has to be installed [18]. A fair policy for clearing of the benefits between the operator of the lead vehicle and

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[20] Assuming an average emission intensity for the EU of 230.7 gCO2eq/kWh [34]. The value of 64 % is obtained for negligible efficiency losses from grid supply to reefer equipment.
[21] Efficiency improvements stem from the fact that three 33-metre-longtrucks can substitute six 16.5-metre-long trucks.
[22] The 4 % efficiency improvement is determined for a speed of 90 km/h and will be lower at slower speed.
[23] The efficiency gain is based on a platoon velocity of 70 km/h. The efficiency gain can higher for higher velocities

those driving within the platoon would also need to be developed. In contrast, a freight train constitutes a 50-truck-long platoon by design, without the need of further technical developments due to the rigid coupling of the wagons.

The efficiency gain through aerodynamic optimisation depends on the **vehicle's velocity**, since the aerodynamic drag increases quadratically with speed. Besides aerodynamic design improvements, some European countries – such as Germany – already only permit maximum speeds of 80 km/h for heavy trucks, while others are considering a reduction of the maximum speed from 90 km/h to 80 km/h[24] for trucks with a gross weight above 7.5 t [92]. This measure would increase the efficiency as the aerodynamic drag is reduced by 21 % resulting in a fuel saving and emission reduction potential of 5 % to 15 % [93]. On a side note, this would also improve road safety, as the released energy by an unbraked collision would decrease by 25 % for decreased velocity [94]. In contrast, a reduced maximum speed would diminish the benefits achievable through aerodynamic techniques and devices. A uniformly lower maximum permitted speed of 80 km/h for trucks could have an impact on engine configuration, as a lower maximum speed affects the power requirement of the engine and possibly leads to a more efficient powertrain.

[24] This 11 % reduction in speed would lead to a 21 % reduction in aerodynamic drag.

4. Conclusions

Combined transport is 40 %–70 % more efficient than road freight transport already today, but it is not yet fully zero-carbon. In this study, the energy efficiency and emissions aspects presented for the different transport modes. Intermodal techniques are combined in order to obtain a full picture for the entire door-to-door transport chain and to provide an outlook for zero-carbon door-to-door CT.

4.1 Zero-carbon door-to-door road-rail combined transport

The transport sector currently contributes almost 30 % of the EU's annual GHG emissions – hence the transition to sustainable transportation solutions is a key challenge and requires action to meet the European climate targets.

Within freight transport, road-rail CT distinguishes itself through higher energy efficiency and lower emissions due to the characteristics of the participating modes – even zero-carbon CT door-to-door is feasible with the technologies available in the market already today. As such, modal shift can serve as a KPI to measure the progress towards more sustainable freight transport, in addition to being used specifically as a steering parameter for legislation and regulation.

Transport on road legs in CT – because of their short distances – can already be operated fully electric with BEVs based on today's battery technology. While BEVs are locally emission-free, zero-carbon road legs can be achieved also in a WtW perspective by using green electricity. Regarding the currently still limited availability of green electricity, the focus on transport technologies with high energy efficiency is important – and BEVs perform better in this regard than current conventional diesel trucks. FCEVs also show comparatively low WtW emissions when using green hydrogen, although the production, distribution, and onboard conversion of hydrogen is less efficient than the direct use of electricity in BEVs – in fact FCEVs powered by green hydrogen consume three times more electricity [95]. In summary, today's BEVs neither pose obstacles from a technical nor an operational perspective, which is why they are predestined for use on road legs in CT.

As the TEN-T core network is already electrified to a very large extent, transport on the rail leg can already be considered zero-carbon in a TtW perspective. Some European railway undertakings, such as Metrans or Rail Cargo Group [96, 97] for example, are already using green traction electricity to provide zero-carbon transport offers in a WtW perspective in selected countries where green electricity is available. Rail transport is inherently more efficient than road transport due to a low rolling resistance, aerodynamic advantages, and route topology. Regarding energy efficiency, further improvements can be achieved by using longer trains (740 m or longer) and implementation of DAC to allow for regenerative braking and the use of grid power on the individual wagons.

The efficiency of transhipment and the associated emissions depend substantially on the degree of electrification of transhipment terminals, while their electrification fundamentally depends on the availability of electric-powered equipment for the different intermodal techniques. As of today, RMGs, which are typically used to perform transhipment in the largest terminals, are already electrified whereas RTGs, reach stackers, and terminals tractors are mainly powered by diesel engines. However, electric alternatives are increasingly becoming available on the market. Equipment for horizontal transhipment such as CargoBeamer, Modalohr, or RoLa are already powered by electricity today. Regarding shunting, there is currently no serial production of battery-electric shunting locomotives. However, the technological prerequisites are already in place. Through terminals that can be accessed via swing entry by line locomotives, such as or Cargo City Vienna South [98]or Megahub Lehrte [99], do not require shunting, which – in case of using green electricity – enables zero-carbon transhipment already today.

In conclusion, the technology for zero-carbon door-to-door CT is available, but completely zero-carbon CT services are not yet widespread. However, for selected relations such as Megahub Lehrte to Cargo City Vienna South, zero-carbon door-to-door CT is possible already today.

4.2 Outlook for zero-carbon door-to-door combined transport

Important steps on the way to zero-carbon door-to-door CT are the proliferation of electric trucks and the increasing market maturity of electric equipment for transhipment and shunting. Presently, high purchase prices due to expensive battery packs and low production volumes pose an obstacle, although there are already initiatives by various stakeholders to address this. The battery price is projected to decrease over time, and several manufacturers have committed to ambitious targets for the BEV share of their total production which may stimulate the production ramp-up. Furthermore, subsidy programmes to support the acquisition and/or the operation of electric trucks and equipment exist, such the EU’s Connecting Europe Facility as well as incentives such as those provided for in the revised Eurovignette Directive [100].

Both from a technical and operational point of view, charging facilities must be installed to allow the use of battery electric trucks and equipment without significantly disrupting operations. In that respect, charging of BEVs during a terminal visit of 30–60 minutes can be a good option. Terminal equipment might be charged during periods of low utilisation due to the cyclical operation of terminals. Electric RTGs do not require charging but are grid-powered through a busbar or a cable reel.

Electrification of railway main lines is not a challenge within the TEN-T core network, but already rather the standard. Some non-core network lines often used by freight trains should nevertheless still be electrified. The pathway to zero-carbon rail transport depends on the decrease in emission intensity of electricity generation in Europe. In order not to exhaust renewable electricity, the further increase of transports energy efficiency is a goal achievable through rail transport – with the revised TEN-T regulation acting as the roadmap for this.

With regard to the challenges posed by the climate crisis, the essential aim is to reduce GHG emissions as quickly as possible. The necessary emission reduction from the transport sector cannot effectively be achieved by improvements within the modal silos but rather by creating bridges between the silos to achieve the inclusion of modes that are inherently more efficient and have the potential of being completely zero-carbon already today. The assessment in this study showed, that with today's technologies, zero-carbon door-to-door CT is possible. Consequently, it is now necessary to take the appropriate actions to proceed into the direction of a widespread zero-carbon combined transport network.

References

[1] V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, Y. Chen, L. G. I. Goldfarb, J. Matthews, S. Berger, M. Huang, O. Yelekçi, R. Yu, B. Zhou, E. Lonnoy, T. K. Maycock, T. Waterfield, K. Leitzell and N. Claud, "Summary for Policymakers," *Climate Change 2021: The Physical Science Basis. Contribution of Working Group 1 to the Sixth Assessment Report of the Intergouvernmental Panel on Climate Change,* 2021.

[2] IPCC, "Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, Cambridge , 2022.

[3] European Comission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, De Vita A., Capros P., Paroussos L., Fragkiadakis K., Karkatsoulis P., Höglund-Isaksson L., "EU reference scenario 2020 : energy, transport and GHG emissions : trends to 2050.," 16 07 2021. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/96c2ca82-e85e-11eb-93a8-01aa75ed71a1/language-en/format-PDF/source-219903975. [Accessed 08 03 2022].

[4] European Comission, "The European Green Deal," *COM(2019) 640*, 2019.

[5] REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT, "European Climate Law," *Official Journal of the European Union,* no. 2021/1119, 2021.

[6] eurostat, "Freight transport statistics - modal split," 02 2021. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split. [Accessed 11 04 2022].

[7] K. Jörling, "Modal Shift Policy in Switzerland," Navigant, 03 09 2019. [Online]. Available: https://www.euki.de/wp-content/uploads/2019/09/20180827_CH_Modal-shift_Study.pdf. [Accessed 11 04 2022].

[8] L. H. Kaack, P. Vaishnav, M. G. Morgan, I. L. Azevedo and S. Rai, "Decarbonizing intraregional freight systems with a focus on modal shift.," *Environmental Research Letters,* vol. 8, no. 13, 2018.

[9] d-fine GmbH, "Combined Transport: carbon footprint and energy efficiency," 2021. [Online]. Available: Combined Transport: carbon footprint and energy efficiency. [Accessed 08 03 2022].

[10] A. Evans, V. Strezov and T. J. Evans, "Assessment of sustainability indicators for renewable energy technologies.," *Renewable and sustainable energy reviews,* vol. 13, no. 5, pp. 1082-1088, 2009.

[11] International Energy Agency, "www.uic.org," 2015. [Online]. Available: https://uic.org/IMG/pdf/iea-uic_2015-2.pdf. [Accessed 02 03 2022].

[12] Z. Gao, Z. Lin and O. Franzese, "Energy consumption and cost savings of truck electrification for heavy-duty vehicle applications," *Transportation Research Record,* vol. 2628, no. 1, pp. 99-109, 2017.

[13] eurostat, "Freight transport statistics - modal split," 7 7 2021. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/1142.pdf#:~:text=Modal%20split%20in%20the%20EU%20Road%20transport%20continues,reached%20a%20new%20high%20since%202008%2C%20accounting%20for. [Accessed 03 03 2022].

[14] P. Tipler and G. Mosca, Physik, Berlin Heidelberg: Springer-Verlag, 2015.

[15] E. J. Saltzman and R. R. J. Meyer, "A Reassessment of Heavy-Duty Truck Aerodynamic Design Features and Priorities," [Online]. Available: https://www.nasa.gov/centers/dryden/pdf/88628main_H-2283.pdf. [Accessed 02 03 2022].

[16] J. Turner, "Resistance is futile: how aerodynamics inform train design," Railway Technology, 04 11 2013. [Online]. Available: https://www.railway-technology.com/features/feature-aerodynamic-train-design-arrowedge-union-pacific-bombardier-zefiro/. [Accessed 02 03 2022].

[17] B. MacAuliffe, M. Lammert, X.-Y. Lu, S. Shladover, M.-D. Surcel and A. Kailas, "Influences on Energy Savings of Heavy Trucks Using Cooperative Adaptive Cruise Control," *SAE Technical Paper 2018-01-1181,* 2018.

[18] A. Ghosal, S. U. Sagong, S. Halder, K. Sahabandu, M. Conti, R. Poovendran and L. Bushnell, "Truck platoon security: State-of-the-art and road ahead.," *Computer Networks,* vol. 105, 2021.

[19] hansewaggon, "Information on the 740 meter freight train," 02 02 2021. [Online]. Available: https://www.hanse-waggon.de/infos-zum-740-meter-gueterzug/. [Accessed 08 03 2022].

[20] S. Tsugawa, "An overview on an automated truck platoon within the energy ITS project.," *IFAC Proceedings* , vol. 46, no. 21, pp. 41-46, 2013.

[21] Q. Liu, M. Xu, C. S. P. Mao and Q. Wang, "Energy-efficient control of freight trains on steep gradients," in *37th Chinese Control Conference*, Wuhan, 2018.

[22] H. Ferreira, C. M. Rodrigues and C. Pinho, "Impact of road geometry on vehicle energy consumption and CO2 emissions: An energy-efficiency rating methodology.," *Energies,* vol. 13, no. 1, p. 119, 2020.

[23] Transport Intelligence, "Europe's road freight market short of more than 400,000 drivers," 21 08 2021. [Online]. Available: https://www.ti-insight.com/briefs/europes-road-freight-market-short-of-more-400000-drivers/. [Accessed 03 03 2022].

[24] KombiConsult GmbH, Intermodality Ltd, PLANCO Consulting GmbH,Gruppo CLAS S.p.A., "Analysis of the EU Combined Transport," European Comission, Frankfurt, 2015.

[25] R. W. Howarth and M. Z. Jacobsen, "How green is blue hydrogen?," *Modelling And Any,* vol. 10, no. 9, pp. 1676-1687, 2021.

[26] N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle and K. Shine, "Atmospheric implications of increased Hydrogen use," Department for Business, Energy & Industrial Strategy, London, 2022.

[27] Frazer-Nash Conultancy, "Fugitive Hydrogen Emissions in a Future Hydrogen Economy," Department for Business, Energy & Industrial Strategy, London, 2022.

[28] Fraunhofer Institut, “Wasserstoffantriebe für E-Scooter und Co.,” 01 02 2021. [Online]. Available: https://www.fraunhofer.de/de/presse/presseinformationen/2021/februar-2021/wasserstoffantriebe-fuer-e-scooter-und-co.html. [Accessed 20 04 2022].

[29] M. Hommen and M. Reichardt, “Oberleitungs-Lkw: erste Bilanz zum Hybrid-Scania,” 24 06 2019. [Online]. Available: https://www.automobil-industrie.vogel.de/oberleitungs-lkw-erste-bilanz-zum-hybrid-scania-a-840532/. [Accessed 04 05 2022].

[30] A. Chalmin, “CCUS: Kann abgeschiedener Kohlenstoff sinnvoll genutzt werden?,” 2020 07 2020. [Online]. Available: https://www.boell.de/de/2020/07/30/ccus-kann-abgeschiedener-kohlenstoff-sinnvoll-genutzt-werden. [Accessed 14 03 202].

[31] A. Burkert, “Endenergiebezogene Analyse Diesel versus Elektromobilität,” 24 08 2021. [Online]. Available: https://www.springerprofessional.de/elektromobilitaet/dieselmotor/endenergiebezogene-analyse-diesel-versus-elektromobilitaet/16673694. [Accessed 11 03 2022].

[32] A. Rödl, C. Wulf and M. Kaltschmitt, “Assessment of selected hydrogen supply chains—factors determining the overall ghg emissions.,” *Hydrogen supply chains,* pp. 81-109, 2018.

[33] A. L. S. Basile and A. Iulianelli, "Membrane reactors for methane steam reforming (MSR).," *Membrane reactors for energy applications and basic chemical production.,* pp. 31-59, 2015.

[34] European Environment Agency, "Greenhouse gas emission intensity of electricity generation by country," European Environment Agency, 25 10 2021. [Online]. Available: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-9/#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111. [Accessed 07 03 2022].

[35] M. Röck, R. Martin and S. Hausberger, “JEC Tank-To-Wheels report v5: Heavy duty vehicles,” Publications Office of the European Union, Luxembourg, 2020.

[36] M. Prussi, M. Yugo, L. De Prada, M. Padella, R. Edwards and L. Lonza, “JEC Well-to-Tank report v5,” Publications Office of the European Union, Luxembourg, 2020.

[37] Bosch, "Bosch und Weichai Power steigern Wirkungsgrad von Weichai Lkw-Dieselmotor auf 50 Prozent," 16 09 2020. [Online]. Available: https://www.bosch-presse.de/pressportal/de/de/bosch-und-weichai-power-steigern-wirkungsgrad-von-weichai-lkw-dieselmotor-auf-50-prozent-218880.html. [Accessed 11 03 2022].

[38] P. Zsófia, “Volvo Trucks announce new electric models with a range of 300 km,” 05 11 2020. [Online]. Available: https://trans.info/en/volvo-trucks-announce-new-electric-trucks-with-a-range-of-300-km-207658. [Accessed 16 03 2022].

[39] VDI/VDE, “Brennstoffzellen- und Batteriefahrzeuge - Bedeutung für die Elektromobilität,” 2019.

[40] Office of Energy Efficiency & Renewable Energy, “Physical Hydrogen Storage,” [Online]. Available: https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage. [Accessed 20 04 2022].

[41] Y. Li, M. Bi, B. Li, Y. Zhou, L. Huang and W. Gao, “Explosion hazard evaluation of renewable hydrogen/ammonia/air fuels,” *Energy,* vol. 159, pp. 252-263, 2018.

[42] F. Huneke, C. P. Linkenheil and M. Niggemeier, “KALTE DUNKELFLAUTE - ROBUSTHEIT DES STROMSYSTEMS BEI EXTREMWETTER,” Greenpease Energy eG, Berlin, 2017.

[43] M. Aziz, T. Oda and T. Kashiwagi, “Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy,” *Energy Procedia,* vol. 158, pp. 4086-4091, 2019.

[44] G. Zubiabc, R. Dufo-Lópeza, M. Carvalhob and G. Pasaogluc, "The lithium-ion battery: State of the art and future perspectives," *Renewable and Sustainable Energy Reviews,* vol. 89, pp. 292-308, 2018.

[45] H. Hao, Y. Geng, J. E. Tate, F. Liu, K. Chen, X. Sun and F. Zhao, “Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment.,” *Nature communications,* vol. 10, no. 1, pp. 1-7, 2019.

[46] K. M. Abraham, “How comparable are sodium-ion batteries to lithium-ion counterparts?.,” *ACS Energy Letters,* vol. 5, no. 11, pp. 3533-3547, 2020.

[47] NAIMA, "WHAT NAIMA IS," [Online]. Available: https://naimaproject.eu/what-naima-is/. [Accessed 15 03 2022].

[48] Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT, "ELuStat: Iron-air battery as stationary energy storage," [Online]. Available: https://www.umsicht.fraunhofer.de/en/projects/iron-air-battery.html. [Accessed 15 03 2022].

[49] B. Kennedy, D. Patterson and S. Camilleri, “Use of lithium-ion batteries in electric vehicles.,” *Journal of Power Sources,* vol. 90, no. 3, pp. 156-162, 2000.

[50] S. Yu, S. Schmohl, Z. Liu, M. Hoffmeyer, N. Schön, F. Hausen and R. A. Eichel, “Insights into a layered hybrid solid electrolyte and its application in long lifespan high-voltage all-solid-state lithium batteries.,” *Journal of Materials Chemistry A,* vol. 7, no. 8, pp. 3882-3894, 2019.

[51] M. Vousen, “How far away are mass-market solid-state EV batteries?,” 14 03 2022. [Online]. Available: https://www.just-auto.com/features/how-far-away-are-mass-market-solid-state-ev-batteries/. [Accessed 11 04 2022].

[52] Large, 23 03 2021. [Online]. Available: https://www.large.net/news/8ku43mw.html. [Accessed 09 03 2022].

[53] Battery University, “BU-205: Types of Lithium-ion,” 22 10 2021. [Online]. Available: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion. [Accessed 09 03 2022].

[54] Batterie2020, 2020. [Online]. Available: https://batterie-2020.de/lexikon/natrium-nickelchlorid-batterie/. [Accessed 09 03 2022].

[55] R. D. McKerracher, C. Ponce de Leon, R. G. A. Wills, A. A. Shah and F. C. Walsh, “ A review of the iron–air secondary battery for energy storage.,” *ChemPlusChem,* vol. 80, no. 2, pp. 323-335, 2015.

[56] J. Y. Hwang, S. T. Myung and Y. K. Sun, “Sodium-ion batteries: present and future.,” *Chemical Society Reviews,* vol. 46, no. 12, pp. 3529-3614, 2017.

[57] Capital Equipmnt News, 14 09 2020. [Online]. Available: XCS45-EV . [Accessed 15 03 2020].

[58] Terberg special Vehicles, “Next generation electric terminal tractors,” [Online]. Available: https://www.terbergspecialvehicles.com/en/development/electric/. [Accessed 15 93 2022].

[59] COMMUNICATION FROM THE COMMISSION, “'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality,” vol. COM(2021) 550 final, 2021.

[60] European Union, “Connecting Europe Facility (CEF) Call for proposals,” 16 09 2021. [Online]. Available: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/cef/wp-call/2021/call-fiche_cef-t-2021-compcoen_en.pdf. [Accessed 24 03 2022].

[61] Kalmar, “Kalmar Ottawa T2E+ Electric Terminal Tractor and shunt trucks,” 2022. [Online]. Available: https://www.kalmarglobal.com/equipment-services/terminal-tractors/ottawa-electric-terminal-tractor-t2e/. [Accessed 29 03 2022].

[62] United States Environmental Protection Agency, “Greenhouse Gases Equivalencies Calculator - Calculations and References,” [Online]. Available: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references. [Accessed 29 03 2022].

[63] M. Sisson, “ELECTRIC YARD TRACTORS WEIGHING THE COSTS AND BENEFITS,” 2017. [Online]. Available: https://wpassets.porttechnology.org/wp-content/uploads/2019/05/25183522/068-069_Electric_Yard_Tractors_Weighing_the_Costs_and_Benefits.pdf. [Accessed 29 03 2022].

[64] Kalmar, [Online]. Available: https://www.kalmarglobal.com/4a5435/globalassets/media/216562/216562_Kalmar-Eco-RST-ENG-Brochure-Web.pdf. [Accessed 31 03 2022].

[65] K. Kusakaka, “Optimal energy management of a hybrid diesel generator and battery supplying a RTG crane with energy recovery capability,” *Energy Reports,* vol. 7, pp. 4769-4778, 2021.

[66] R. B. Mitja Klemenčič, “Data base and comparative analysis of CT and transhipment technologies for CT,” Interreg Alpine Space, 2018.

[67] freightquip, [Online]. Available: https://freightquip.com/product-category/rail/shunt-vehicles/lok-electric-shunt-vehicles/. [Accessed 01 04 2022].

[68] Port of Rotterdam, “First zero-emission, full-electric shunting locomotives for Port of Rotterdam in production,” 23 06 2021. [Online]. Available: https://www.portofrotterdam.com/en/news-and-press-releases/first-zero-emission-full-electric-shunting-locomotives-for-port-of. [Accessed 2022 03 25].

[69] railmagazine, 22 03 2022. [Online]. Available: https://www.railmagazine.com/news/network/2022/03/22/moveable-electrification-system-could-replace-diesel-shunting. [Accessed 11 04 2022].

[70] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, “REGULATION (EU) No 1315/2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU,” 2013.

[71] E. Commission, “Progress report on implementation of the TEN-T network in 2016-2017,” 2020.

[72] W. Schade, W. Rothengatter, M. Stich, M. Streif, M. Himmelsbach, N. Lindberg, C. d. Stasio, F. Fermi, S. Maffii, L. Zani, D. Bielanska and I. Skinner, “Analysis accompanying the Impact Assessment for the revision of Regulation (EU) N° 1315/2013 – FINAL REPORT,” Report on behalf of the European Commission, Karlsruhe, Milano, 2021.

[73] European Comission, “Sixth report on monitoring development of the rail market,” European Comission, Brussels, 2019.

[74] German Federal Ministry of Transport and Digital Infrastrucutre, “The 2030 Federal Transport Infrastructure Plan,” 2016.

[75] Deutsche Umwelthilfe e.V., “Hintergrundpapier | DUH-Projekt „Lückenschluss“,” 2020.

[76] H. Basma, A. Saboori and F. Rodríguez, "TOTAL COST OF OWNERSHIP FOR TRACTOR-TRAILERS IN EUROPE: BATTERY ELECTRIC VERSUS DIESEL," International Council on Clean Transportation , 2021.

[77] F. Hacker, R. Blanck, W. Görz, T. Bernecker, J. Speiser, F. Röckle, M. Schubert and G. Nebauer, “Bewertung und Einführungsstrategien für oberleitungsgebundene schwere Nutzfahrzeuge,” Berlin, 2022.

[78] Volvo, 04 03 2022. [Online]. Available: https://stpi.it.volvo.com/STPIFiles/Volvo/ModelRange/fh42t3a_deu_ger.pdf. [Accessed 31 03 2022].

[79] Volvo, 09 03 2022. [Online]. Available: https://stpi.it.volvo.com/STPIFiles/Volvo/ModelRange/fm42t1a_deu_ger.pdf. [Accessed 31 03 2022].

[80] L. Mauler, F. Duffner, W. G. Zeier and J. Leker, “Battery cost forecasting: a review of methods and results with an outlook to 2050,” *Energy & Environmental Science.,* 2021.

[81] Allianz pro Schiene, “Überblick: Wie der Güterzug länger werden kann,” 30 08 2016. [Online]. Available: https://www.allianz-pro-schiene.de/themen/aktuell/740-meter-gueterzug/. [Accessed 08 04 2022].

[82] Ministerial Declaration, “Rail Freight Corridors: The Future of Rail Freight in Europe,” in *Ministerial Conference “Innovative Rail Transport – connecting, sustainable,*, Berlin, 2020.

[83] A. Pyper and P. S. Heyns, “Pyper, A., & Heyns, P. S. (2019). Evaluating a distributed regenerative braking system for freight trains,” *Journal of Rail and Rapid Transit,* vol. 233, no. 8, pp. 844-856, 2019.

[84] S. Hagenlocher, P. Wittenbrink, C. Leuchtmann, B. Galonske, T. Kehrmann, M. Hecht, M. Leiste, S. Discher, R. König, T. Pollehn, M. Ruf, S. Witte, S. Gehrke, R. Hess, K. Röckemann and A. Steinmetz, “Development of a concept for the EU-wide migration to a digital automatic coupling system (DAC) for rail freight transportation,” Bundesministerium für Verkehr und figitale Infrastruktur, Karlsruhe, 2020.

[85] Gensetpower, [Online]. Available: https://www.gensetpower.com/quality-11966484-15kw-clip-on-carrier-type-reefer-container-generator-40-feet-silent-diesel-genset. [Accessed 31 03 2022].

[86] Hardy Diesel, “Diesel Generator Fuel Consumption Chart,” [Online]. Available: https://hardydiesel.com/resources/diesel-generator-fuel-consumption-chart/. [Accessed 31 03 2022].

[87] M. Irzik, T. Kranz, J.-A. Bühne, K.-P. Glaeser, S. Limbeck, J. Gail, W. Bartolomaeus, A. Wolf, C. Sistenich, I. Kaundinya, I. Jungfeld, U. Ellmers, J. Kübler, H. Holte and R. Kaschner, " Feldversuch mit Lang-Lkw: Abschlussbericht.," Bundesanstalt für Straßenwesen, Bergisch Gladbach, 2018.

[88] VDA, "Lang-Lkw: Kostengünstige Lösung, um CO_2-Emissionen zu reduzieren," [Online]. Available: https://www.vda.de/de/themen/automobilindustrie/nutzfahrzeuge/lang-lkw. [Accessed 06 04 2022].

[89] L. Cider and S. Ranäng, "Final report DUO2-Trailer," 2014.

[90] F. Dünnebeil, C. Reinhard, U. Lambrecht, A. Kies, S. Hausberger and M. Rexeis, "Future measures for fuel savings and GHG reduction of heavy duty vehicles," Umweltbundesamt, Dessau-Roßlau, 2015.

[91] A. Alam, *Fuel-efficient heavy-duty vehicle platooning,* Stockholm: KTH Royal Institute of Technology, 2014.

[92] Fraktion BÜNDNIS 90/DIE GRÜNEN, "Für ein einheitliches Lkw-Tempolimit von 80 km/h auf Autobahnen in Europa," 06 07 2011. [Online]. Available: https://dserver.bundestag.de/btd/17/064/1706480.pdf. [Accessed 08 04 2022].

[93] L. I. Panis, I. De Vlieger, L. Pelkmans and L. Schrooten, "Effect of speed reduction on emissions of heavy duty lorries.," *Highway and Urban Environment,* pp. 53-61, 2007.

[94] Wissenschaftliche Dienste des deuteschen Bundestags, "Tempolimit für LKW auf Bundesautobahnen und Anforderungen an die Bremssysteme," 22 9 2022. [Online]. Available: https://www.bundestag.de/resource/blob/883948/a6d0c71b6c88b7babcef0deb56df0b90/WD-5-010-22-pdf-data.pdf. [Accessed 06 04 2022].

[95] Scania, "Scania's commitment to battery electric vehicles," 19 01 2021. [Online]. Available: https://www.scania.com/group/en/home/newsroom/news/2021/Scanias-commitment-to-battery-electric-vehicles.html. [Accessed 19 01 2022].

[96] M. v. Leijen, "Green electricity for all RCG trains in Germany," 15 01 2021. [Online]. Available: https://www.railfreight.com/technology/2021/01/15/green-electricity-for-all-rcg-trains-in-germany/. [Accessed 12 04 2022].

[97] Metrans, "METRANS Trains Get 100 % CO2 Free," [Online]. Available: https://metrans.eu/metrans-trains-get-100-co2-free/. [Accessed 13 04 2022].

[98] Künz, "WienCont, Freudenau - Intermodal Krane," [Online]. Available: https://www.kuenz.com/wp-content/uploads/2021/09/Kuenz_bei_WienCont_de.pdf. [Accessed 22 04 2022].

[99] M. Rathmann, "Erste Zugabfahrt im Megahub Lehrte," 16 06 2020. [Online]. Available: https://www.eurotransport.de/artikel/kombinierter-verkehr-in-neuen-dimensionen-erste-zugabfahrt-im-megahub-lehrte-11163178.html. [Accessed 13 04 2022].

[100] The European Parliament and the Coucil, "Directive (EU) 2022/362 on the charging of vehicles for the use of road infrastructures," 2022.

[101] COMMUNICATION FROM THE COMMISSION, "REPowerEU: Joint European Action for more affordable, secure and sustainable energy," vol. COM(2022) 108 final, 2022.

[102] L. Fendt and B. Hager, "Is there a danger that pumping liquid carbon dioxide underground could have the same negative impacts as fracking?," 21 04 2021. [Online]. Available: https://climate.mit.edu/ask-mit/there-danger-pumping-liquid-carbon-dioxide-underground-could-have-same-negative-impacts. [Accessed 16 03 2022].

[103] electreon, "Wireless charging anywhere is here," [Online]. Available: https://electreon.com/technology. [Accessed 30 03 2022].

[104] Transport & Environment, "How to decarbonise long-haul trucking in Germany. An analysis of," 2021.

[105] Regulation (EU) No 1315/2013 of the European Parliament and of the Council, *Official Journal of the European Union,* no. 1315/2013, 2013.

[106] J. Jöhrens, M. Allekotte, F. Heining, H. Helms, D. Räder, N. Köllermeier and V. Waßmuth, "Vergleichende Analyse der Potentiale von Antriebstechnologien für LKW im Zeithorizont 2030," ifeu, Heidelberg/Karlsruhe, 2022.

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