Decarbonizing Construction Material Supply Chains: An Innovative Approach to Intermodal Transportation

Philipp Miklautsch[1(✉)], Manuel Woschank[1], and Julia Heißenberger[2]

[1] Chair of Industrial Logistics, Montanuniversitaet Leoben, Erzherzog-Johann-Straße 3/1, 8700 Leoben, Austria
philipp.miklautsch@unileoben.ac.at

[2] W. Riedel Silo-Transport GmbH, Triesterstrasse 381, 8401 Feldkirchen bei Graz, Austria
julia.heissenberger@siloriedel.at

Abstract. The transportation of construction materials is a crucial part of the construction material supply chain and a major contributor to greenhouse gas emissions from transportation. In Austria, for example, around 11% of the goods transported in 2020 were mineral products, such as glass, cement, lime, and plaster - much of which are demanded by the construction industry. Some of those goods are bulk materials that are well suited for high-capacity means of transport, e.g., trains. However, several system characteristics of the railroad severely limit its use on the last mile to the customer. Here, materials need to be delivered in a timely and efficient manner to ensure that projects stay on schedule and within budget. An eligible solution for this is intermodal transportation, which couples the benefits of efficient rail haulage with flexible road haulage. Nevertheless, conventionally used 30-foot silo containers hinder high utilization of trains due to weight limit excess of trucks. Therefore, a novel 22.5-foot container design for the transportation of cement was introduced recently that enables a high-capacity utilization of trucks and trains. In this article, we present the environmental impact of its use in construction material transportation by quantifying greenhouse gas emissions of an exemplary use case in the Austrian construction industry. Results show emission mitigation potentials of 75% to 93%, depending on several parameters. This article contributes to the scientific literature by bringing evidence on emission reduction potentials in the construction material supply chain and elaborating on the determining factors.

Keywords: combined transport · construction material · industrial logistics · climate change · greenhouse gas emissions

1 Introduction

The Synthesis Report for the Sixth Assessment Report of the IPCC draws a clear and alarming call for urgent action to reduce greenhouse gas (GHG) emissions

J. Fottner et al. (Eds.): CLEaR 2023, LNCE 390, pp. 123–136, 2024.
https://doi.org/10.1007/978-3-031-44021-2_14

in the coming decade to hinder the most threatening and irreversible impacts of climate change on humanity. According to the report, emissions need to peak before 2025, highlighting the necessity to implement near-term mitigation actions on time [1].

Investigating the sources of global GHG emissions shows that the transportation sector accounts for around 15–16% [2,3], being one of the hardest sectors to decarbonize [4]. Especially regarding freight transportation, the choice of effective near-term measures is limited. Literature and practice intensively discuss various methods to power future vehicles with renewable energy, the most famous of which being electricity and hydrogen. Although these options are promising and inevitable in the long-term, they are not expected to have a significant impact in the coming years in any of the world's regions [4]. Nevertheless, the avoidance of unnecessary transportation operations through consolidation and bundling, as well as the shift away from road transportation to less carbon-intensive modes were shown to have deep carbon emission reduction potentials [5] and are thus promising for near-term decarbonization.

In Europe, the infrastructure for railways is well-established [6], indicating that the shift towards rail transportation is a viable option in the European Union. However, several barriers impede the transition to rail transport. One obstacle is that the number of direct connections from manufacturing companies to the railroad is declining, indicating that only a small number of consignees and consignors have direct access to the rail network [6]. Furthermore, train deliveries are scheduled - and sometimes delayed, which makes them less flexible, making it difficult to achieve Just-in-Time (JIT) shipments [7]. Challenges regarding the access to the rail network and the timeliness can thereby be overcome by utilizing combined road-rail transportation (CRRT). It allows for the first or last mile to be flexibly transported by truck, and the goods to be buffered at the terminals and delivered JIT. The main challenge in CRRT is thereby the efficient cargo transshipment between the two modes of transport [8] to minimize the break-even distance [9], as well as the utilization of railway cars and truck trailers with the same load unit. Nevertheless, the railway system was initially installed - and is still optimized - for the transportation of heavy and bulky goods over long distances [10]. Regarding the construction material supply chains (CMSC), rail transportation is thus best suited for materials such as cement, lime, and plaster. In Austria, those goods account for around 11% of the goods transported in 2020 [11]. To ensure a flexible delivery, they are mostly transported in silo containers - which scored poorly in terms of their intermodal capabilities.

To increase the efficiency of CRRT for silo transportation, a new load carrier design was introduced lately by InnoFreight Solutions GmbH, which is tailored to the typical customers' needs. The "CemTainer" was specifically designed to transport cement via CRRT. On the one hand, it enables efficient handling and, on the other hand, the full utilization of railway cars and trucks. To investigate the environmental impact of CRRT usage in the CMSC, we elaborate the GHG emissions in an exemplary transport chain of cement in Austria. For practitioners, results provide an insight in the emission reduction potential of CRRT in short- to medium-distance transportation in the CMSC. For researchers, results indicate further research directions and point to weaknesses in current emission quantification guidelines when applied to CRRT.

In the following section, the results of an initial literature review are presented briefly. Subsequently, the exemplary transport chain and the methodology to quantify GHG emissions are outlined, followed by its results and a brief discussion.

2 Literature Review

2.1 Green Transportation in the Construction Material Supply Chain

Logistics and transportation are crucial aspects for the success of a construction project as they impact the delivery time, cost, and quality of the materials (e.g., [12]). Thus, optimization of the CMSC can increase construction projects' resilience [13]. Besides economic aspects, the environmental footprint of construction projects is a rising issue for researchers and practitioners (e.g., [14]). Green transportation was found to be one key element of reducing environmental impacts of construction projects (e.g., [15]). Thereby, a main research stream concentrates on logistics network measures to enhance freight consolidation and bundling. Initially introduced to deal with rising traffic congestion issues (e.g., [16]), bundling and consolidation are meanwhile an important part of reducing transportation costs and emissions. For example, Construction Consolidation Centres enjoy increasing popularity, being intended to relieve inner-city traffic and reduce the environmental impacts of urban CMSC transportation activities [17]. Besides those approaches, construction material transportation practitioners report, for example, on introducing circular approaches for pallets [18], highlighting the relevance to focus on improving existing logistics structures towards sustainability.

2.2 Combined Transportation

The term "combined transport" refers to a method of transporting goods that involves consolidating them at regional hubs, transporting them to another hub in a different region, and redistributing them to local nodes. While this type of transportation generally involves at least two modes [19], European legislation defines specific combinations of modes that qualify as combined transport. Thereby, combined transport needs to involve truck transportation on the first and/or last leg, and transportation by rail, inland waterway, or maritime services on the main leg. Furthermore, it is required that solely lorries, trailers, semi-trailers (with or without a tractor unit), swap bodies, or containers of 20 ft or more are transshipped [20].

Using combined transportation for bulk materials is preferred for long-distance routes, for example in inter-state grain silo transportation [21], as the specific costs of the train are 30–35% lower than those of road freight [9]. Thus, the efficiency of the transshipment activities at hubs defines the length of the break-even distance and is thereby one determining factor of the competitiveness of CRRT [8]. Another decisive factor is the utilization of vehicles, as a higher load reduces specific costs of good transportation, and thus overall logistics costs (see, e.g., [22]). Nevertheless, using CRRT complicates the transport chain, as more parties are involved. This implies an increased risk of longer delivery times, which can be contradictory to JIT and has to be monitored carefully [23].

2.3 A Novel Load Carrier Design

Due to the aforementioned aspects, this article elaborates on different options to use a novel load carrier design for CRRT in CMSC. Information regarding the so-called "CemTainer" was provided to the authors by internal documents. The CemTainer is a 22.5 ft-long container with a C22 profile, equipped with standard interfaces for handling and transport. This profile is common for intermodal load carriers, as it is also used in 30 ft open-top containers [24], the 30 ft AgroTainer [25] or the 20 ft ChemieTainer [26]. The high volume of 32 m^3 and the compact design allows the maximum permissible total weight of the trucks to be utilized while maximizing the number of containers on the rail car. By providing this combination, both means of transport in CRRT can be utilized to their full capacity, enabling cost-competitive combined transport. The standard handling interfaces allow for little handling fees, as they can be handled by reach stackers or gantry cranes. Last-mile truck transport and the possibility of pressure unloading by tipping the CemTainer make its use flexible for different customer sites, also in urban areas and on construction sites. As the typical customers for cement silo transportation are large construction sites or concrete plants with high demand, the large delivery volume further meets the customers' needs.

3 Methodology

In the following section, we present the evaluation of GHG emissions with different scenario configurations. First, the scenarios and the parameter variation are described. Subsequently, the methodology to calculate emissions is discussed.

3.1 Description of the Scenarios

The scenarios evaluated in this article are based on a real-world case from an Austrian transport company specializing in silo transportation. The focal case thereby describes the transportation of cement from one cement plant to different customers like concrete plants or large construction sites. To simplify the calculation, we assume a representative customer in the center of gravity of all possible customers as the transport destination. Since the area of possible customers is close to an urban center, this consideration hardly distorts the results. In Fig. 1, the two transport chain configurations are visualized.

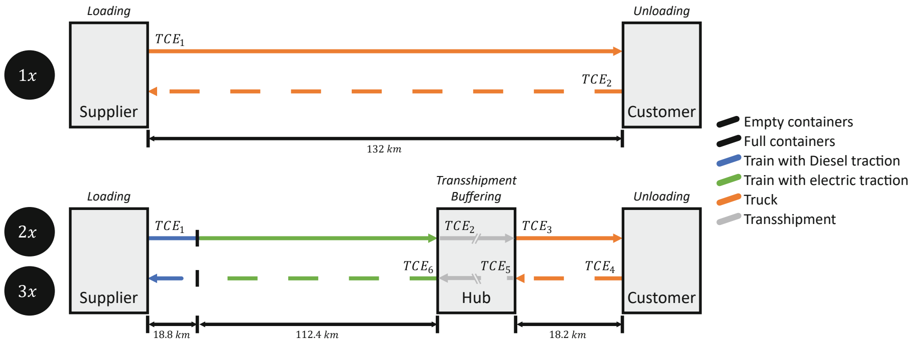

Fig. 1. An overview of the scenarios covered

Scenarios 1*a* to 1*c* represent the base case, conducting transportation by truck only. Thereby, the maximum permissible cement weight is loaded onto the truck at the cement plant and a distance of $d_1 = 132$ km must be driven by road. Currently, there is no possibility to refill the load carriers near the customers and backhaul goods, which necessitates the empty trip of $d_1 = 132$ km back to the cement plant.

Scenarios 2*a* to 2*c* and 3*a* to 3*c* represent the CRRT case, shifting the main leg to rail while still delivering the goods JIT to the customers through truck transportation on the last mile. The train line includes an unelectrified branch line that connects the plant to the electrified main line, which results in a total rail distance of $d_{2,rail} = 131.2$ km. As the hub is located slightly outside the city centre, the truck needs to drive another $d_{2,road} = 18.2$ km, which results in a slightly increased overall distance traveled of $(d_{2,rail} + d_{2,road}) - d_1 = 149.4$ km for the containers in the CRRT scenarios.

The connecting entity between those two transport modes is the hub, having a transshipment and a buffering function. Transshipment equipment thereby stores incoming full containers from the train in a buffer zone and - when requested - loads those units on trucks driving to the customers. Conversely, empty containers from the customers are buffered at the hub until a block train takes them back to the cement plant. As all containers cycle through this loop, four hub operations are necessary for each container: the full container is transshipped from the train to the buffer zone from the buffer zone to the truck. Similarly, the empty container is transshipped from the truck to the buffer zone and from the buffer zone to the train. According to [27], these operations need to be included in the emission calculation of intermodal transport chains. The emissions thereby depend on the energy consumption and the fuel emission intensity - which depends on the type of equipment used. Thus, scenarios 2*x* and 3*x* differentiate by the main handling equipment in the hubs. Hub operations in the scenarios 2*x* are conducted by Diesel-powered reach stackers, whereby hubs in the scenarios 3*x* use electrified rail-mounted gantry cranes (RMGC).

Besides shifting transport from road to rail, another frequently discussed measure to decarbonize transportation is the usage of alternative fuels and drivetrains [5]. Thus, for each scenario group $1x$, $2x$ and $3x$, we compare three possible combinations of such: First, the a-scenarios present the base case, using conventional internal combustion engines with Diesel B7 (Diesel with about 7% Biodiesel share). Second, the b-scenarios use Hydrotreated Vegetable Oil (HVO), an advanced biofuel that can be used in conventional internal combustion engines. Third, trucks in the c-scenarios are powered by electric drivetrains. Table 2 in the appendix provides an overview of the scenario parameters.

3.2 GHG Emission Quantification

To quantify GHG emissions from the transport chain, we adhere to [27]. It requires breaking down the transport chain into "the discrete, sequential transport chain elements (TCEs) that reflect the related vehicle types, pipelines or hubs that carry, handle or transfer the freight and/or the passengers as part of the whole transport chain" [27], p. 19). Each TCE is either a hub operation of a certain hub operation category (HOC) or a transport operation of a transport operation category (TOC). Each HOC or TOC thereby defines a set of operations with similar characteristics regarding the transport mode, hub type and freight type. Different energy carriers can be used in a TOC, which is why we define the TOCs as follows:

- $TOC_{t,d}(fuel)$: Truck delivery of one container from the cargo consignor to the cargo consignee or vice versa, whereby the truck is powered by $fuel$
- $TOC_{r,c}$: Rail delivery of several containers from the cargo consignor to the hub or vice versa
- $TOC_{t,c}(fuel)$: Truck delivery of one container from the hub to the cargo consignee or vice versa, whereby the truck is powered by $fuel$

A HOC shall group hub activities according to their characteristics, e.g., the number or the nature of hub operations included in the HOC. As of these requirements, we define two HOCs for our scenarios:

- HOC_{RS}: Unloading a container from an incoming vehicle, transporting it to an interim storage location, receiving it from this location, and loading it to the outgoing vehicle - by using a Diesel-powered reach stacker.
- HOC_{RMGC}: Unloading a container from an incoming vehicle, transporting it to an interim storage location, receiving it from this location, and loading it to the outgoing vehicle - by using an electrified RMGC.

We thereby define the transport chains as presented in Table 3 in the appendix and model the emissions by a bottom-up energy-based approach [27]. With this approach, for each TOC, the emissions of all energy consumers involved in the activities A_i of the TOC are summed up - taking into account the emissions of the vehicle energy provision

$$G_{VEP,TOC,A_i} = Q_{TOC,A_i} \times \epsilon_{VEP,A_i}$$

as well as the emissions of the vehicle operation

$$G_{VO,TOC,A_i} = Q_{TOC,A_i} \times \epsilon_{VO,A_i}$$

Thereby, Q_{TOC,A_i} is the quantity of GHG activity type A_i, e.g., the amount of Diesel or electricity, ϵ_{VEP,A_i} is the emission intensity of energy provision, and ϵ_{VO,A_i} is the emission intensity of the vehicle operation phase. Summed up, $G_{TOC} = \sum_i G_{VEP,TOC,A_i} + \sum_i G_{VO,TOC,A_i}$ provides the emissions of the TOC. A similar approach is considered for the hub operations. In the following paragraphs, we elaborate on the most important parameters for the quantification of GHG emissions throughout the scenarios. For the calculation spreadsheet including the detailed references refer to the appendix.

Energy Consumption Data: Energy consumption data Q of the transportation equipment is taken from the EcoTransIT methodology report [28], Table 22 and Table 26. For the energy consumption of the hub equipment, we requested internal information from our partners, which we were able to cross-validate by different publications. For details, see the calculation spreadsheet which is linked in the appendix.

GHG Intensity of Diesel B7: In Austria, the Diesel sold in 2021 had an average Biodiesel share of 6.02% concerning the energy content [29]. Considering data from [30], this results in a GHG intensity of $\epsilon_{B7} = \epsilon_{VO,B7} + \epsilon_{VEP,B7} = 88.51\, gCO_2e/MJ = 3.16\, kgCO_2e/l$.

GHG Intensity of HVO: To be eligible as a transportation biofuel, a fuels' emission intensity must be 65% lower than the reference value of 94 gCO_2e/MJ, which leads to a maximum permissible emission intensity of $\epsilon_{HVO} = \epsilon_{VO,HVO} + \epsilon_{VEP,HVO} = 32.90\, gCO_2e/MJ$ [31]. The actual emission factor depends on the specific fuel used. The authors were provided HVO certificates proving that emissions can be lowered by 85% to 13.2 gCO_2e/MJ. Nevertheless, as these reductions are rather uncertain, we use the conservative upper boundary for our estimations - possibly overestimating the emissions from the *b*-scenarios.

GHG Intensity of Electricity: Different emission factors for electricity are available, an excerpt of which can be found in Table 4 in the appendix. Due to the multiplicity of possible references, we use the emission factor published by the Austrian Environmental Agency [32] for road transportation by electric vehicles $\epsilon_{E_{truck}} = \epsilon_{VEP,E_{truck}} = 17.666\, gCO_2e/MJ$. The usage of this reference is also required by the Austrian Fuel Ordinance to calculate the emission intensity of fuels, which we use for the quantification of HVO emissions. Thus, the value from this source appears to be the most comparable - and the most recent. For railway transportation, we use the factor provided by [28] of $\epsilon_{E_{rail}} = \epsilon_{VEP,E_{rail}} = 49\, gCO_2e/MJ$, as it is the most specific factor we can determine.

4 Results and Discussion

4.1 Results

Table 1 presents the calculation results. Thereby, the emissions of the base-case in scenario $1a$, transportation by truck with conventional fuel, stand out. Fuelling the trucks with pure HVO may thereby decrease emissions by nearly 63%. Replacing the combustion engine with an electric one reduces emissions to about 10% of the base case' ones. The combined transportation scenarios $2a$ to $3c$ highlight a GHG mitigation potential of 75% to 93% - depending on the utilized truck fuel and hub equipment. If RMGC are used for transshipment, the emissions of the transport chain are about 6% points lower than when handling with Diesel-powered reach stackers. This is due to the lower energy consumption and the lower emission intensity of electricity. In Fig. 2 in the appendix, the results of the GHG quantification are visualized.

Table 1. GHG quantification results

Scenario	HOC	Truck fuel	Emissions/$kgCO_2e$		Reduction
			per year	per 1000 kg	
1a	none	Diesel B7	4 238 615.30	10.60	0.00%
1b	none	HVO	1 575 533.20	3.94	62.83%
1c	none	Electricity	427 583.64	1.07	89.91%
2a	HOC_{RS}	Diesel B7	1 032 233.71	2.58	75.65%
2b	HOC_{RS}	HVO	692 582.65	1.73	83.66%
2c	HOC_{RS}	Electricity	545 389.98	1.36	87.13%
3a	HOC_{RMGC}	Diesel B7	779 804.72	1.95	81.60%
3b	HOC_{RMGC}	HVO	440 153.67	1.10	89.62%
3c	HOC_{RMGC}	Electricity	292 960.99	0.73	93.09%

4.2 Discussion

Scenarios 1 and 2 highlight the large emission reduction potential of CRRT when using internal combustion engines in truck operations. As emission intensities of truck operations sink, the impact of hub operations on GHG emissions becomes evident. Thus, the comparison of the c-scenarios is interesting: Once battery electric trucks are broadly utilized, the hub equipment will determine whether CRRT is beneficial or detrimental to the environment on short- to medium-distances. The combination of low emissions from road transport and high emissions from the hub is responsible for the fact that combined transport in scenario $2c$ has more emissions than direct transport by truck in scenario $1c$. Nevertheless, as long as the specific emissions of the train are lower than those of the truck, a certain break-even distance regarding GHG emissions exists, but the transport chain in this paper is too short to reach this distance in scenario $2c$. Furthermore, the effects of Diesel-powered trains becomes visible in this case. The graph of cumulative emissions in the appendix (Fig. 2) in the first section of rail transportation in scenarios $2c$ and $3c$ is steeper than the one in scenario $1a$, highlighting the importance to shift transportation to electrified train tracks. The usage of Diesel-powered trains reduces emissions compared to conventional truck technologies (i.e., in the a- and b-scenarios), but increases emissions compared to battery electric trucks.

4.3 Limitations

Regarding hub operations, we assume only two handling operations per transshipment activity and thereby neglect inter-terminal operations that may be necessary due to the operational characteristics of the terminal. The real number of necessary handling operations to transship one container depends on different factors and differs between terminals. In addition to the number of handling operations, emissions from other operational and administrative activities (e.g., fuel use for inter-terminal transportation or office lightning and heating) are neglected. These depend on the processes of the respective terminal and can vary considerably in some cases. For this reason, we did not investigate the use of lower-carbon alternatives for the hub operations, e.g., HVO-powered reach stackers. Furthermore, the quantification results are sensitive to a change in the input emission intensities ϵ. As mentioned above, HVO could lead to much more savings in practice. Similarly, electricity for the trucks could be used from purely renewable sources, which would reduce emissions even further. Moreover, the rail electricity mix is an average value from [28], which may vary over time and the train operating company.

5 Conclusion

This contribution highlights the potential of two decarbonization measures that are currently underrepresented in the Austrian industrial freight landscape: combined transportation and the use of advanced biofuels. It presents the environmental merits of utilizing a novel load carrier design enabling competitive combined road-rail transportation in the construction material supply chain. Therefore, the GHG emissions in an exemplary transport chain are quantified by using nine scenarios, comparing the utilization of different truck fuels and transshipment equipment. Results show that, compared to direct truck transportation, an emission reduction of 75% to 93% can be reached by using combined road-rail transportation. All scenarios using combined transportation reduce emissions compared to their direct transportation counterparts - except one. In this special scenario, trucks are powered by electricity and the additional Diesel-powered hub operations as well as the non-electrified section of rail transport exceed the lower energy consumpion of electrified rail transportation. Nevertheless, up to the point in time to which battery electric trucks can be utilized broadly, combined road-rail transportation provides a significant short-time emission reduction potential. After this point, hub operations and rail track electrification may play a crucial role in determining how beneficial combined road-rail transportation will be from the environmental perspective.

Acknowledgments. This work was accomplished with intensive support from Silo-Riedel GmbH, who provided details on the exemplary transport chain, Innofreight Solutions GmbH, who provided details on the CemTainer design, as well as Paul Rudolf GmbH, who provided the authors with exemplary data for HVO emission factors.

Appendix

Calculation Spreadsheet

The Excel spreadsheet for the calculation can be found online: https://github.com/pmikla14/crrt-in-cmsc-ghg-quantification/.

Tables

Table 2. Scenario parameter variations

Scenario	Transshipment	Truck fuel
1*a*	None	Diesel B7
1*b*	None	HVO
1*c*	None	Electricity
2*a*	Reach stacker	Diesel B7
2*b*	Reach stacker	HVO
2*c*	Reach stacker	Electricity
3*a*	RMGC	Diesel B7
3*b*	RMGC	HVO
3*c*	RMGC	Electricity

Table 3. Transport chains with their respective transport chain elements and hub/transport operation categories according to [27]

Scenario	TCE	TOC/HOC		
		a	b	c
1	1	$TOC_{t,d}(B7)$	$TOC_{t,d}(HVO)$	$TOC_{t,d}(E)$
	2	$TOC_{t,d}(B7)$	$TOC_{t,d}(HVO)$	$TOC_{t,d}(E)$
2	1	$TOC_{r,c}$	$TOC_{r,c}$	$TOC_{r,c}$
	2	HOC_{RS}	HOC_{RS}	HOC_{RS}
	3	$TOC_{t,c}(B7)$	$TOC_{t,c}(HVO)$	$TOC_{t,c}(E)$
	4	$TOC_{t,c}(B7)$	$TOC_{t,c}(HVO)$	$TOC_{t,c}(E)$
	5	HOC_{RS}	HOC_{RS}	HOC_{RS}
	6	$TOC_{r,c}$	$TOC_{r,c}$	$TOC_{r,c}$
3	1	$TOC_{r,c}$	$TOC_{r,c}$	$TOC_{r,c}$
	2	HOC_{RMGC}	HOC_{RMGC}	HOC_{RMGC}
	3	$TOC_{t,c}(B7)$	$TOC_{t,c}(HVO)$	$TOC_{t,c}(E)$
	4	$TOC_{t,c}(B7)$	$TOC_{t,c}(HVO)$	$TOC_{t,c}(E)$
	5	HOC_{RMGC}	HOC_{RMGC}	HOC_{RMGC}
	6	$TOC_{r,c}$	$TOC_{r,c}$	$TOC_{r,c}$

Table 4. Different GHG emission intensities of electricity for Austria

Reference	Description	Value	Year
EEA 2022 *	Electricity generation	25.55 $gCO_{2e/MJ}$	2021
Scarlat et al. (2022)**	Electricity use	73.33 $gCO_{2e/MJ}$	2019
[28]	Electricity for railway	49.00 $gCO_{2e/MJ}$	–
[32]	Electricity for transportation	17.666 $gCO_{2e/MJ}$	2022

* European Environmental Agency: Greenhouse gas emission intensity of electricity generation in Europe.
https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1
** Scarlat, N., Prussi, M., Padella, M.: Quantification of the carbon intensity of electricity produced and used in europe. Applied Energy 305, 117901 (2022). DOI: 10.1016/j.apenergy.2021.117901

Figures

The subplots of Fig. 2 are grouped by the truck fuel to ensure a comparison between truck transportation and combined transportation. In all scenarios, except 2*c*, emissions from combined transportation are lower than those of sole truck transportation. This is due to low emissions from battery electric trucks and high emissions from hub operations.

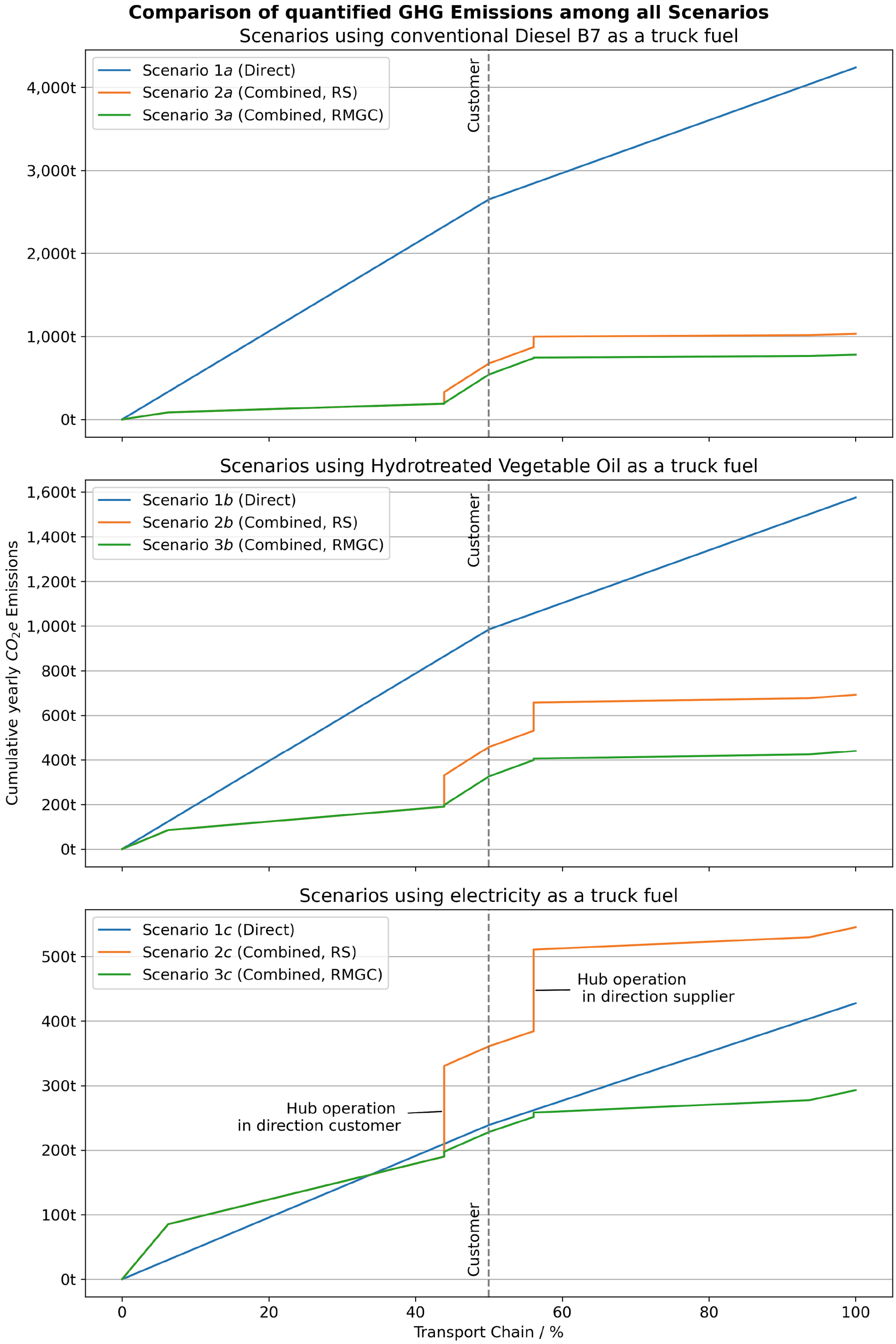

Fig. 2. Cumulative GHG emissions in the nine scenarios, grouped by the truck fuel

References

1. Lee, H., et al.: Synthesis report of the IPCC sixth assessment report (2023). https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf
2. Dhakal, S., et al.: Emissions trends and drivers. In: IPCC (ed.) Climate Change 2022: Mitigation of Climate Change. Cambridge (2022)
3. Ritchie, H., Roser, M.: Co_2 and greenhouse gas emissions. Our World in Data (2020)
4. Jaramillo, P., et al.: Transport. In: IPCC (ed.) Climate Change 2022: Mitigation of Climate Change. Cambridge (2022)
5. Miklautsch, P., Woschank, M.: A framework of measures to mitigate greenhouse gas emissions in freight transport: systematic literature review from a manufacturer's perspective. J. Clean. Prod. **366**, 132883 (2022)
6. UIRR: 2021-22 UIRR Report: European Road-Rail Combined Transport (2022). https://www.uirr.com/uirr-report/
7. Dlugoš, M., Pečený, L., Meško, P., Šulko, P.: The impact of delays of freight trains in JIT system on example one track line. In: MATEC Web of Conferences, vol. 134, p. 00011 (2017)
8. Wucherpfennig, D., Ehret, M., Schoberl, M., Malzacher, G., Bohm, M., Fottner, J.: Model-based systems engineering for the design of an intermodal high-speed freight train terminal. In: 2022 IEEE International Systems Conference (SysCon), pp. 1–8. IEEE (2022)
9. Zgonc, B., Tekavčič, M., Jakšič, M.: The impact of distance on mode choice in freight transport. Eur. Transp. Res. Rev. **11**(1), 1–18 (2019)
10. Rodrigue, J.P.: The Geography of Transport Systems, 5th edn. Routledge, Abingdon, Oxon, New York (2020)
11. Statistik Austria: Verkehrsstatistik 2020 (2021). https://www.statistik.at/wcm/idc/idcplg?IdcService=GET_NATIVE_FILE&RevisionSelectionMethod=LatestReleased&dDocName=127158
12. Liao, L., Yang, C., Quan, L.: Construction supply chain management: a systematic literature review and future development. J. Clean. Prod. **382**, 135230 (2023)
13. Hsu, P.Y., Aurisicchio, M., Angeloudis, P.: Risk-averse supply chain for modular construction projects. Autom. Constr. **106**, 102898 (2019)
14. Backes, J.G., Traverso, M.: Application of life cycle sustainability assessment in the construction sector: a systematic literature review. Processes **9**(7), 1248 (2021)
15. Ali, Y., Saad, T.B., Sabir, M., Muhammad, N., Salman, A., Zeb, K.: Integration of green supply chain management practices in construction supply chain of CPEC. Manage. Environ. Qual.: Int. J. **31**(1), 185–200 (2020)
16. Jourquin, B., Beuthe, M., Demilie, C.L.: Freight bundling network models: methodology and application. Transp. Plan. Technol. **23**(2), 157–177 (1999)
17. Guerlain, C., Renault, S., Ferrero, F.: Understanding construction logistics in urban areas and lowering its environmental impact: a focus on construction consolidation centres. Sustainability **11**(21), 6118 (2019)
18. Xella: How the transport of our building materials is becoming more sustainable (2022). https://news.xella.com/csr/how-the-transport-of-our-building-materials-is-becoming-more-sustainable
19. Crainic, T.G., Kim, K.H.: Chapter 8 intermodal transportation. In: Transportation, Handbooks in Operations Research and Management Science, vol. 14, pp. 467–537. Elsevier (2007)
20. Council of European Union: Council directive 92/106/EEC (1992)

21. Mogale, D.G., Kumar, M., Kumar, S.K., Tiwari, M.K.: Grain silo location-allocation problem with dwell time for optimization of food grain supply chain network. Transp. Res. Part E: Logist. Transp. Rev. **111**, 40–69 (2018)
22. Zsifkovits, H.E.: Logistik, Reihe Grundwissen der Ökonomik, vol. 3673. UVK-Verl.-Ges and UVK/Lucius, Konstanz and München (2013)
23. Kukulski, J., Lewczuk, K., Góra, I., Wasiak, M.: Methodological aspects of risk mapping in multimode transport systems. Eksploatacja Niezawodność – Maintenance Reliab. **25**(1) (2023)
24. Ferrovie Udine Cividale: Cargo at societa ferrovie udine cividale srl (2018). https://www.ferrovieudinecividale.it/wp-content/uploads/2018/12/FUC_folder-cargo_2015.pdf
25. CD Logistics: Types of containers (2023). https://www.cdcargologistics.cz/en/nase-sluzby/system-innofreight/types-containers
26. InnoFreight: Chemietainer 20ft: In intermodal rail/road transport (2021). https://www.innofreight.com/wp-content/uploads/2021/06/ChemieTainer_EN.pdf
27. ISO/FDIS 14083: Greenhouse gases: Quantification and reporting of greenhouse gas emissions arising from transport chain operations (2023). https://www.iso.org/standard/78864.html
28. ETW: Environmental methodology and data: Update 2022 (2022). https://www.ecotransit.org/wordpress/wp-content/uploads/20220908_Methodology_Report_Update_2022_Website.pdf
29. BMK: Biokraftstoffe im verkehrssektor 2021 (2021). https://www.bmk.gv.at/themen/energie/publikationen/biokraftstoffbericht.html
30. ÖNORM EN 16258: Methode zur berechnung und deklaration des energieverbrauchs und der treibhausgasemissionen bei transportdienstleistungen (güter- und personenverkehr) (2012)
31. European Union: Consolidated text: Directive (EU) 2018/2001 of the European parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (text with EEA relevance)text with EEA relevance (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02018L2001-20220607
32. UBA: Anrechnung (erneuerbarer) strom: gem. §11 kraftstoffverordnung (kvo) (2023). https://www.umweltbundesamt.at/elna/anrechnung-erneuerbarer-strom