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Energy Consumption and Greenhouse Gas Emissions Arising from Logistical Activities within the Field of Road Transportation – a Review of Annual Balances and Mitigation Measures

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ABSTRACT

The transport sector is facing challenging transformations in order to reach the climate goals according to the European Green Deal. This review aims to compile a comprehensive set of available energy and greenhouse gas (GHG) emission data to estimate a) road transportation and site-related GHG emissions from logistics companies and b) impacts of mitigation measures discussed in literature. Out of an initial set of 1,050 hits, about 77 publications were identified that provide quantitative values for energy consumption or GHG emissions. The largest part of literature on energy demand and emissions in logistics deals with transport, with 62 out of 77 publications, which accounts for the majority of the energy demand in the logistics sector. The majority of published data is based on individual case analyses and modeling studies, reflecting the heterogeneity of the industry.

As there is no standardized method for collecting GHG emissions for the logistics sector, the system boundaries and quantitative values of the published data vary considerably, making comparisons and evaluations difficult. The most common system boundary is "freight transport within a given area", followed by "logistics site", "vehicle routing", "supply chain" and "corporate footprint". Reported energy and GHG reduction potentials focus on the optimization of building services efficiency, intralogistics processes and transport-related processes (route planning, driving behavior, vehicle efficiency and load factor). The greatest potential for reducing GHG emissions in the logistics sector lies in replacing fossil fuels for trucks with green fuels or electrification, combined with restructuring urban delivery networks. Publications of actual consumption or transport-specific metrics are rare in the literature. The quantitative values reported can only be interpreted correctly if the context in which they occur is specified in terms of a logistics reference value; this is why the effects of the mitigation measures applied also vary in the literature. The further development of standardization in the field of emissions recording by transport companies and the consensus on a uniform reference value are therefore key drivers for the quantification and reduction of GHG emissions in the logistics sector.

KEYWORDS: logistics · energy · GHG emissions · mitigation measures

1 INTRODUCTION

The goals of greenhouse gas (GHG) emission reduction within the European Union are getting more ambitious. Until 2030, the German sector of transportation may only emit less than 35 % of the GHGs referred to in 1990 and has to achieve climate neutrality by 2045 [1]. More than three-quarters of the GHG emissions caused by logistic activities occur during transportation processes [2–7]. Within this context, all logistical activities in Germany, but especially transport logistics, have to become more sustainable. As road transport is not only the most important but also the most carbon-intensive mode of transport in Germany, we limit our literature review to publications related to road transport.

Although the problem is not new and efforts have been made within the last decade, emissions arising from traffic, transportation and logistics are still increasing [8], [9]. One of the issues identified in literature is the fragmentation of responsibilities among supply chains (SCs) and logistical networks, resulting in a general lack of information [10]. A better understanding of GHG emissions – when, why and by whom – is still needed to achieve greater progress towards carbon-neutral logistics.

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The aim of this paper is to describe the status quo of energy consumption and greenhouse gas emissions of logistics activities caused by road transport and associated hubs and storages. The focus of this literature review is on published numerical values for GHG emissions from road transportation. This means that among the articles dealing with combined freight transport, only the part that discusses road transport or directly compares it with another mode of transport is included. Based on this data compilation, we search for reported potentials of applied mitigation measures to lower the energy consumption and resulting GHG emissions.

Knowing the actual level of energy consumption is very important for a logistics company and from a scientific point of view. It is the basis for possible reduction potentials. It is also of interest for all other actors in a supply chain, including but not limited to logistics companies or service providers, to know their own share of total emissions and where they are located. In this paper we want to review the status of published data on quantitative values for energy consumption and resulting GHG emissions for logistics companies, logistics activities such as transportation or infrastructure logistics, and logistics sites such as hubs or warehouses. The GHG emissions of a transport logistics company are very closely linked to its energy consumption because it offers a service and not a material-consuming and waste-creating product. If a logistics company attempts to lower its company carbon footprint, the first step involves the measurement and accounting of emissions generated. Since emissions are not measured directly, a precise knowledge of one's own energy (e. g. fuel) consumption is necessary in order to calculate emissions based on these data. If the levels and generation processes for the GHG emissions are known and can be controlled, mitigation measures can be found to match them. According to the Greenhouse Gas Protocol classification scheme [11], company emissions of different origins can be assigned to a polluter according to its operational boundaries. On the one hand, there are the direct emissions that arise from combustion processes within the company under consideration (scope 1). On the other hand, emissions are also caused by the company's operations elsewhere upstream, such as through electricity production (scope 2). Finally, there are "scope 3 emissions [that] are a consequence of the activities of the company, but occur from sources not owned or controlled by the company" [11], for example, emissions caused by employee commuting (scope 3).

According to the accounting framework for transport emissions of the Intergovernmental Panel on Climate Change (IPCC) [12], transport emissions can be described by transport mode (road, rail, waterways, air), fuel intensity (carbon equivalent of fuel used), energy intensity (transport efficiency) and sufficiency. EN 16258 offers a general methodology for the calculation and declaration of energy consumption and GHG emissions of transport services for freight and passenger transports [13].

Companies tend to publish their data in self-reports, such as environmental or sustainability reports, which cover accumulated data over several sites and multiple transport routes and means of transportation. Different sustainability reports of the industry show a wide diversity regarding the level of detail, scope and methods applied [14–17]. Data extracted from those reports is accordingly difficult to compare and evaluate. Against this background, we are interested in the extended question of whether data from scientific publications can be used to derive key indicators for energy consumption and GHG emissions of logistics companies, sites or processes, against which specific companies can then be compared or to which tailored emission-reducing measures can be assigned.

The review examines whether energy or emission studies of logistics activities published in literature follow the same motivation and if published results on quantitative data and mitigation measures are transferable to different companies and locations.

In detail, we want to answer the following questions:

- What methods are used for data acquisition?
- Which system boundaries are applied? Do studies focus on road transportation or site activities, and do they include scope 1, scope 2 or even scope 3 emissions?
- What is the logistics context of the data and mitigation measures published?
- Is it possible to derive key figures for energy requirements and GHG emissions of core logistics processes from the literature published?
- What are the mitigation measures concerning GHG emissions that are currently recommended? Does research provide transferable quantitative results for different mitigation measures? Does the literature provide consistent suggestions on how transportation logistics must evolve to reach net-zero GHG emissions?

2 MATERIALS AND METHODS

2.1 Literature Review Design

The literature review includes all specific publications on energy, emissions, sites and road transport processes. The main selection criteria for scientific publications are the specific information of quantitative values provided for energy consumption and/or GHG emissions, arising from any logistical activities, together with the data describing the scope to which this consumption or emission is related. These could be:

– Annual energy consumption of the site as a whole or per tonnage handled

– Energy consumption for internal transports with floor trucks, forklifts, high-bay storage systems

– Energy consumption of freezing technology or refrigeration

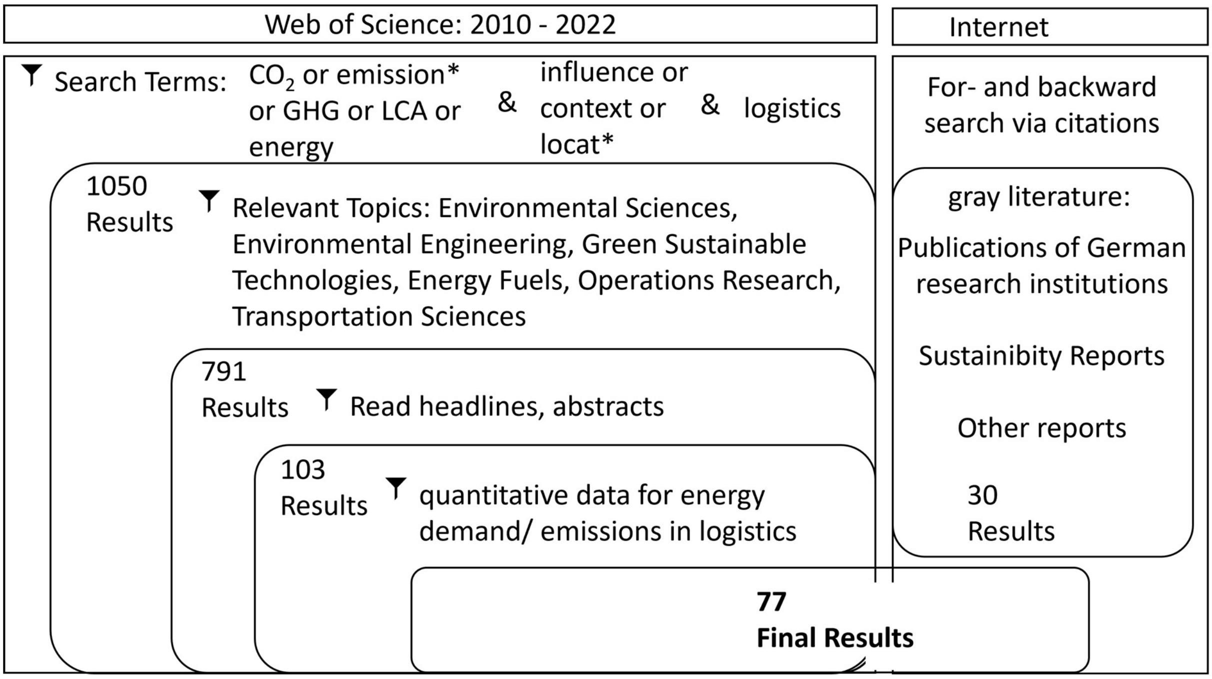

Fig. 1: Search matrix and results of the systematic literature search performed

– Energy consumption for road transport (fuels) per tkm (tonne * kilometer)
– Specific information about GHG emissions following the same scheme as energy consumption, supplemented by information about emission factors, quotes of renewable energy sources used, and reference frames or scopes applied

The review is based on a systematic literature search of scientific publications in the English and German language. Scientific publications from 2010 to 2022 were analyzed following the filtering scheme shown in Figure 1. A combination of “CO_2”, “emission*”, “life cycle assessment (LCA)”, “energy” or “GHG” with “logistics” and “influence” or “context” or “locat*” was applied as initial search topics. The resulting 1,050 hits were further filtered regarding the general topic of the publication. Inclusion criteria were quantitative data on energy consumption, GHG emissions, or reduction potentials both for transportation and on-site activities. The paper focuses on road transportation, therefore, publications on shipping, air and rail freight were excluded. Reverse logistics and research topics covering closed-loop logistics were also excluded in the title analysis. After analyzing titles, keywords, abstracts and conclusions, 103 candidate papers remained, of which 38 report quantitative data. In the next step, a forward and backward search based on the paper’s citations and a search in the gray literature was carried out. Regarding the gray literature, 20 research reports of German research institutions and 6 logistics companies’ own reports, such as environmental or sustainability reports, were exemplarily included. Company reports that provide information on the total GHG share from transport, but not on the carbon dioxide equivalent (CO_2e) share attributable to other logistics processes, are excluded from this review. The final number of 77 publications present the portfolio of this review.

2.2 Content Analysis and Clustering

The published papers of the final portfolio can be clustered by different aspects to analyze the findings of different publications better. The heterogenous background of the selected literature becomes obvious, especially when the geographical background to which the published data refers is taken into account.

2.2.1 Data Accounting Method

The portfolio is limited to publications which give quantitative data on either the energy demand or GHG emissions of logistics processes and, where applicable, mitigation measures, thus, the published papers can be classified according to the data accounting method:
– Case study: individual cases of the research topic in real-life contexts; often empirically collected
– Analytical: mathematical modeling, numerical examples that are build up with a bottom-up approach described by analytical equations
– Simulation: analysis and test of the response of a proposed model by scenario analyses

The input data themselves can originate from different types of sources: for example, empirical surveys, such as interviews or measurements, statistical data sets, generic data derived from standards, manufacturer’s data on energy and fuel consumption.

Table 1: CO_2 equivalents from transports after IPCC, transport p. 604 [12]

mode tkm_{mode}/tkm_{total}	fuel intensity f CO_2e/MJ	energy intensity e MJ/tkm	activity a tkm_{total}
transport via	**carbon content**	**efficiency**	**sufficiency**
road rail waterways air space pipeline	diesel gasoline fossil CNG / LNG biomethane hydrogen electricity	capacity curb weights utilization traffic/driving situation vehicle efficiency	number of trips distances

2.2.2 System Boundaries

The respective reference frame is important to interpret published data values. In logistics, all processes can, in a first step, be clustered into transportation- or site-related processes.

Transport Emissions

Transport emissions within the review are further analyzed according to the IPCC framework [12]. The IPCC disassembles the GHG emissions into a sum of emissions from the different traffic modes (see Table 1), while this review focuses on road transport.

Each summand is composed of three factors:

– The fuel intensity *f*, defined mainly by the fuel's carbon content, resulting from all CO_2e emissions when combusting the fuel,

– The energy intensity *e*, stating how much energy is needed to perform the transport service of 1 tonne (t) along 1 kilometer (km), and

– The activity *a*, describing the amount of service as transport performance in tkm.

According to EN 16258, transport emissions can be further subclassified into direct (tank-to-wheel: TTW) and indirect emissions (well-to-tank), depending on the respective system boundaries applied [13].

Site-related Emissions

Logistics sites within this review can be hubs, warehouses or distribution centers. Energy consumption and resulting GHG emissions can be clustered by their point of origin:

– Heating, ventilation, cooling/refrigeration of the logistics building

– Equipment such as lighting, IT services

– Infra-logistics activities such as order picking or shipping

When transferring the IPCC transport scheme to on-site processes, *f* (Table 1) is generalized to the amount of CO_2e per unit of energy. This can be thermal energy, electricity or fuel.

According to the Greenhouse Gas Protocol classification scheme [11], site-related emissions can be subclassified depending on the respective system boundaries applied:

– Scope 1 Emissions: Direct emissions from burning fuel for heating/cooling activities and intralogistics, for example, leakage of refrigerants where applicable

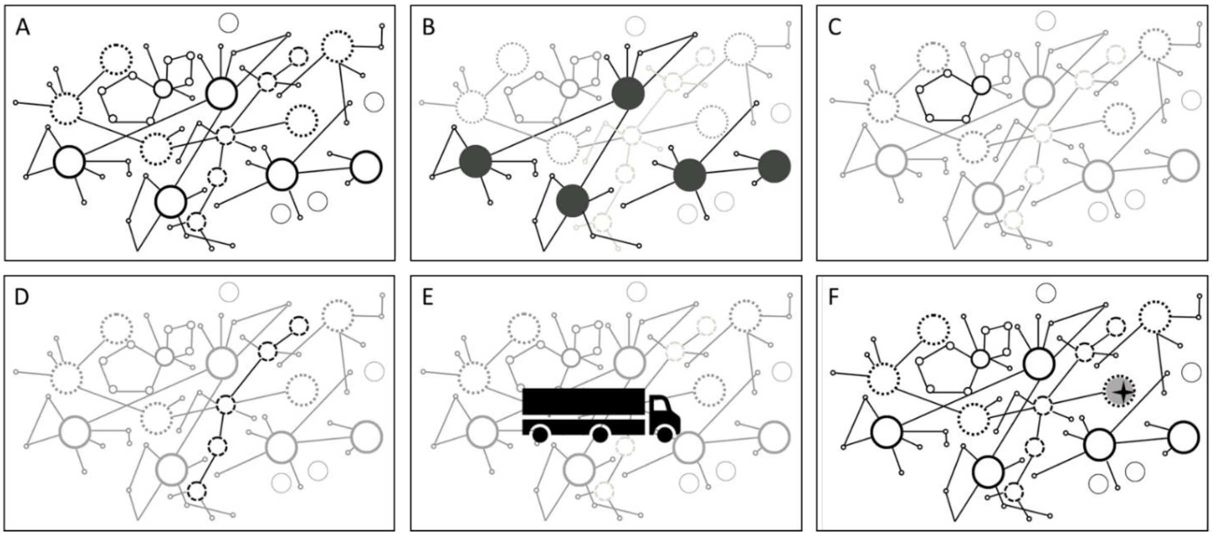

Fig. 2: Context-based reference frames for energy and emissions accounting found in literature

– Scope 2 Emissions: Indirect upstream emissions of energy provision
– Scope 3 Emissions: All other indirect upstream emissions

2.2.3 Logistics Context of Published Data and Mitigation Measures

An intermediate evaluation of the literature portfolio showed the strong heterogeneity of the scientific publications. It became obvious that the logistics context the authors explored influences both the methodology of the data accounting and system boundaries applied.

The following context frames, see Figure 2, are proposed and applied within this review for the further clustering:
– Publications on transport emissions with an area view (Frame A)
– Publications on company carbon footprints (Frame B)
– Publications on transport emissions of one specific route of a logistics provider (Frame C)
– Publications on product carbon footprints along the supply chain (Frame D)
– Publications on vehicle-related emissions (Frame E)
– Publications on site-related energy consumptions and emissions for a single logistics site or their specific logistics processes (Frame F)

3 RESULTS

This review analyses publications on energy consumption and emissions of logistics, i. e. from site-and transportation-related activities. A selection of 77 publications met the requirements of providing quantitative data. In a first step, these results are clustered. In a second step, the publications in the different clusters are evaluated and analyzed.

3.1 Classification of Publications

Each of the selected publications is unambiguously assigned to one of the frames A – F that best fits the selected scope of the publication. Table 2 shows the distribution. The geographical background of the published data shows the worldwide interest of the topic in the scientific discourse. The logistical activities that were the core of the scientific investigation are also listed in Table 2. They could not be clearly assigned (papers deal with 1, 2 or 3 activities) and demonstrate the different scope of the scientific literature. The selected papers were classified into the following groups:
– Long-distance transportation: Data refers to transportation in heavy duty vehicles
– First/last mile transportation: Data describe first or last mile activities using smaller trucks, vans, or cargo bicycles, sometimes in combination with network design and/or routing.
– Network design: Quantifies changes in energy demand and/or GHG emissions as a function of network design/constellation
– Routing: Papers deal with a (sub)type of the vehicle routing problem, addressing energy demand and/or GHG output as a function of the route that vehicles might choose for their transportation tasks.
– Training: The influence of driving personnel on fuel consumption or the influence of on-site personnel on energy demand after training measures (“eco-driving”, “eco-training”) will be evaluated.
– Building services: The focus is on heating, air conditioning, lighting and other non-specific processes related to the building (see also Figure 3). Note that refrigeration is treated as a separate group.
– Production: Major parts of the publication deal with quantitative data related to production. Logistics is discussed as part of a product life cycle.
– Cold chain: The focus is on temperatures below 4°C and the resulting energy demand and/or GHG emissions, also in combination with routing or storage activities.
– Intralogistics: Data is related to material handling and/or conveying processes

The identified literature portfolio covers a wide variety of perspectives and research goals: from the influence of speed and traffic flow on diesel consumption [18] through lighting options in warehouses [19] to optimizing handling speeds of stacker cranes [20]. The heterogenous structure of logistics processes results in different system boundaries in nearly every publication, which makes it difficult to compare published results or even to transfer mitigation results. Normalization of the results is very difficult because there is no common reference to which the emissions can be assigned. Therefore, the published numerical values can be found unaggregated in Tables 3 to 8 under the respective reference frames A – F. The GHG emission reduction values are given as a percentage of the status quo described in the respective paper. Their range, from negative values or close to 1 % up to 96 %, shows that a single scale would not be appropriate to classify results with non-comparable background data. In order to allow an assessment of the GHG reductions achieved, Tables 3 to 8 provide a brief description of the circumstances (system boundaries, benchmarks) under which these reductions were achieved in the respective papers. Common categories to account for emissions and identify mitigation measures are described by [9, 21, 22] or [23] for logistics site emissions and by the IPCC emission framework for transportation. Within the literature portfolio investigated, 23 publications are based on case studies, 16 on analytical considerations and 38 present modeling and simulation results.

A total of 42 publications of the literature portfolio investigates only transport-related emissions, while 15 focus on site-related emissions. Within these clusters, the system boundaries regarded and the aim of the published studies vary. We, thus, apply a context-

Table 2: Final portfolio of selected papers that provide quantitative data (77 publications)

Logistics Context	Transport-related data on energy consumption and emissions				Vehicle-related data	Site-related
Frames	A	B	C	D	E	F
Paper count	21	9	11	10	11	15
Geographical background	USA 7 [25], [26], [99], [35], [112], [113], [114] Germany 5 [115], [29], [116], [90], [117] Portugal 2 [21], [30] China 2 [32], [118] Alp region 1 [119] Australia 1 [120] Brazil 1 [113] Colombia 1 [113] France 1 [31] Japan 1 [22] UK 1 [34]	Germany 5 [16], [18], [33], [40], [41] Austria 1 [7] Belgium 1 [37] Colombia 1 [38] Denmark 1 [14] Singapore 1 [121]	China 2 [55], [52] India 2 [61], [53] Italy 2 [56], [62] USA 2 [43], [59] Austria 1 [60] Canada 1 [27] Portugal 1 [58]	Germany 2 [68], [70] UK 2 [66], [71] worldwide 2 [65], [64] Austria 1 [7] Belgium 1 [66] China 1 [122] East Asia 1 [69] France 1 [66] Indonesia 1 [67]	Germany 6 [72], [73], [78], [76], [78], [123] UK 2 [124], [97], Austria 1 [74] Europe 1 [77] The Netherlands 1 [125]	Germany 10 [81], [19], [20], [126], [102], [127], [6], [83], [84], [86] Italy 2 [3], [82] China 1 [105] Colombia 1 [96] Eastern Europe 1 [23]
Logistic activities in focus	First/last mile transportation 14 [25], [21], [29], [30], [31], [34], [120], [128], [113], [90], [99], [117], [114], [118] Long haul transportation 12 [8], [25], [26], [22], [99], [35], [32], [112], [119], [90], [117], [118]	Long haul transportation 5 [16], [18], [33], [37], [14] First/last mile transportation 3 [18], [38], [121] Network design 3 [16], [33], [37] buildings services 2 [40], [41] Training 2 [40], [41] Routing 1 [38]	First/last mile transportation 8 [61], [60], [55], [56], [58], [43], [27], [62] Network design 4 [60], [43], [52], [27] Routing 3 [61], [55], [53] Long haul transportation 2 [53], [59] Cold chain 1 [53]	Long haul transportation 6 [65], [69], [64], [70], [122], [7] Network design 6 [67], [68], [65], [69], [64], [70] First/last mile transportation 4 [66], [71], [122], [7] Production 3 [65], [69], [64] Cold chain 2 [66], [122]	Long haul transportation 6 [72], [74], [77], [78], [125], [124] Training 3 [123], [78], [97]	Intralogistics 8 [20], [6], [82], [83], [86], [105], [96], [129], All site-related activities 3 [3], [84], [102] Buildings services 3 [19], [82], [86] All storage-related activities 3 [81], [6], [86] Cold chain 1 [82] Warehouse management 2 [23], [96] Warehouse design 1 [126]

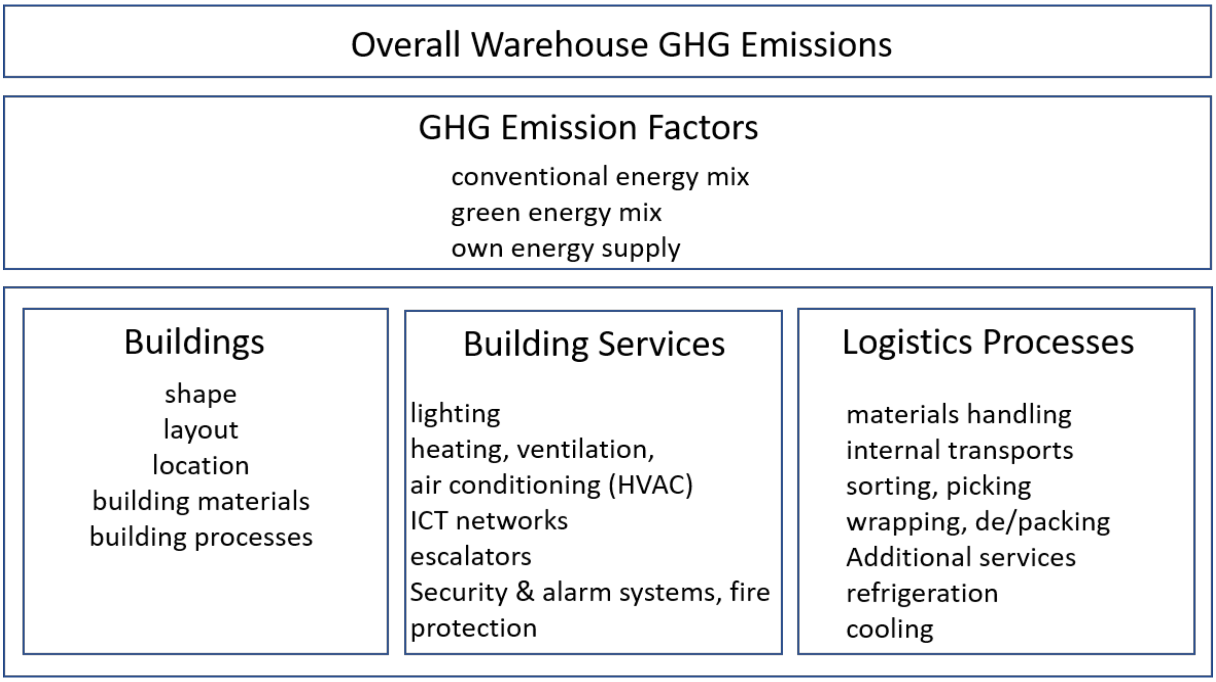

Fig. 3: Framework for mitigation potentials of total GHG emissions of logistics sites as reported in literature

based scheme of categories, which considers both the logistic activities regarded and the system boundaries chosen for each publication. Figure 2 gives an overview of the context-based reference frames for energy and emissions accounting found in literature.

Within the cluster of transportation emissions, 11 publications focus on the vehicle itself, 11 regard transport routes of single logistics companies and 21 describe transportation-related emissions in certain regions. Within the cluster of site-related emissions, 15 publications deal with energy consumption and/or emissions of logistics sites, such as hubs or warehouses, including single measures for energy reduction. Nine publications regard both transport and site emissions from a company carbon footprint perspective, including overall emissions of different locations and all transport activities of a company. Ten publications describe product carbon footprints along supply chains.

3.2 Publications on Transport Emissions with an Area View (Frame A)

The literature included in this frame refers to a logistics region as a whole. This could be a port, a country or a city. All transport of all logistics providers within a certain area are included, but not the energy consumption of the depots/logistical sites. Table 3 shows the 21 publications in this category that includes 3 “gray” literature sources.

Emission inventory reports of the traffic or transportation sector typically take this perspective. Macroscopic, highly aggregated data sets are of interest. These offer the possibility of assessing the infrastructural needs of a region, such as electricity or road networks, and the total reduction potential, or of evaluating policies, taxes, traffic concepts or other macroeconomic measures to reach a reduction of energy consumption or GHG emissions. If available in a time-resolved format, this data can be used to plan ahead for peak demand. Frame “A”, applied to a large area, such as a country, reveals macroscopic effects on the overall freight transport energy efficiency, for example, the structure of commodities that are being transported within that area [24].

As with all views on the development of GHG balances, there are both bottom-up and top-down approaches. The latter uses macroscopic data sets, such as overall fuel consumption, often estimated by fuels produced or sold within the area of interest, or flows of vehicles or freight through the area studied. The first approach uses micro traffic models for a vehicle or a road that are combined with macroscopic data, for example, traffic flows at certain measuring points. Both long-distance [25, 26] and urban logistics [21] take advantage of better traffic flows, in terms of performance (less waiting/traveling times, fewer accidents) and sustainability (less energy consumption, and GHG, nitrogen and particle emissions). This topic is also discussed under the perspective of a vehicle in frame “E.”

The majority of the publications covering city logistics that are included in this review can be assigned to frame “A.” Among these, the replacement of conventional vans is the most common topic. Electric vehicles seem to be an alternative providing environmental benefits because of the lower vehicle capacities and operating ranges needed in urban

*Table 3: Analyses of publications on transport emission with an area view (context frame A).
The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework:
f: fuel intensity, e: energy intensity, a: activity*

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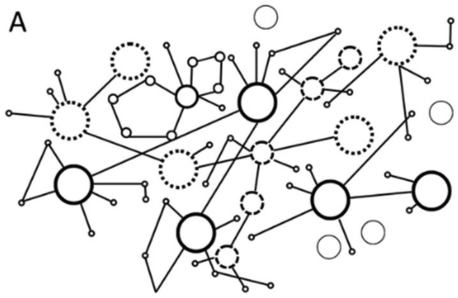
<tr><td colspan="2">
</td><td colspan="4">Area View
21 Publications</td></tr>
<tr><th>Authors</th><th>Logistic activities in focus</th><th>Context</th><th>Quantitative Data on energy consumption or GHG emission mitigations</th><th>Method</th><th>IPCC factor</th></tr>
<tr><td>Rathmann [8]</td><td>mainly long haul transportation</td><td>Statistical macro data sets of Germanys traffic sector, modeled with TREMOD</td><td>No mitigation, status quo of final energy consumption of freight transport in Germany: 106 % (2005 reference year), growing tendency</td><td>simulation</td><td>-</td></tr>
<tr><td>Barth and Boriboonsomsin [25]</td><td>long haul transportation, first /last mile transportation</td><td>Driving without congestion: adherence to a fictitious speed limit of 60 mph</td><td>7 %, in California</td><td>analytical</td><td>E</td></tr>
<tr><td></td><td>long haul transportation, first /last mile transportation</td><td>Variable speed limits to smooth stop-and-go shock waves</td><td>12 %, in California</td><td>analytical</td><td>E</td></tr>
<tr><td>Muratori et al [26]</td><td>long haul transportation</td><td>Platooning – reduce driving resistance</td><td>4.2 % with platooning 65 % of all miles driven by combination trucks in the USA (55mph)</td><td>analytical</td><td>E</td></tr>
<tr><td>Melo et al [21]</td><td>first /last mile transportation</td><td>Sharing of parking spaces between city logistics and kindergarten</td><td>Less stops and better traffic flow, parking time limit 10 min: 3.7 % less GHG, from 432 to 416 kg CO$_2$e/day in one street, Porto, Portugal</td><td>simulation</td><td>E</td></tr>
<tr><td>González Palencia et al [22]</td><td>mainly long haul transportation</td><td>Aggressive promotion of battery electric freight vehicles</td><td>43.9 % compared to a baseline scenario in 2050 in Japan (~35 Mt CO$_2$e/a)</td><td>analytical</td><td>F</td></tr>
</table>

Llorca and Moeckel [29]	first /last mile transportation	In an urban area for parcels <10 kg: Electric cargo bikes and 50 % of the remaining vans electric	40 %, in Munich, Germany	simulation	F
Melo and Baptista [30]	first /last mile transportation	Electric cargo bikes instead of urban delivery vans	10 % vans replaced by electric cargo bikes without changing network performance: ~17 % less energy in network within peak hour. 100 % cargo bikes instead of vans: 73 % less GHG emissions from logistics operators at peak hour (746 kg CO_2e avoided), Porto, Portugal	simulation	f, (e)
Lee et al [99]	Mainly first /last mile transportation	Comparison of life cycle energy demand between diesel and electric trucks in cities of the USA	28 % less energy (3.49 vs 4.86 MJ/t·km), 38 % less GHG (0.24 vs 0.38 kgCO_2e/t·km), USA	analytical	f, (e)
Gonzales-Feliu [31]	first /last mile transportation	Changing urban retail strategies in 4 scenarios: better traffic flow (fuel efficiency) and fewer miles traveled	92 % (from 6150 t CO_2e/week) through bundling trips: 15 transhipment points on the outskirts of the city, pick-up points in the city center, France	simulation	a, e
McLeod et al [34]	first /last mile transportation	1 carrier instead of 10, reduction of vans and distances traveled	42 % for B2B, 61 % for B2C carriers, UK	simulation	A
Craig et al [35]	long haul transportation	Modal shift	46 % (from 125 to 70 g CO_2e/(t·mile)), USA	case study	E
Jiang et al [32]	Mainly long haul transportation	Multimodal transport strategies in an urban agglomeration	55 % in a generic agglomeration of three cities, China	simulation	f, e
Aljohani and Thompson [120]	first /last mile transportation	Impacts of relocating a market on GHG emissions; survey among wholesalers and retailers about distances traveled	No mitigation, status quo after relocation: additional 830 t CO_2e, Melbourne, Australia	case study	A

Assmann et al [128]	first /last mile transportation	Comparison of urban transhipment centers vs. direct deliveries with vans, e-vans, trucks and cargo bikes with different population densities, transhipment center placing, parcel sizes and load factors	Depends strongly on vehicle network constellation; maximum 66 % GHG emission savings possible with urban transhipment centers and cargo bikes, Germany	simulation	f, e
Foytik and Robinson [112]	long haul transportation	Cost-minimizing routing with additional CO_2 cost constraints	0.61 % (8.8 t) for total truck traffic network of one region, USA	simulation	a, (e)
Holguín-Veras et al [130]	first /last mile transportation	Off-hour deliveries: impact on emissions in New York / Bogotá / Sao Paulo	10/30/70 % CO_2 (not CO_2e) emissions savings	simulation	E
Nocera and Cavallaro [119]	long haul transportation	Detour reduction through harmonized transnational crossing exchange, toll and emission trading system in the alp region	From 2,304 to 1,691 t CO_2e in total transalpine region by crossing exchange: 27 %	simulation	A
Wildemann and Specht [90]	long haul transportation, first /last mile transportation	Shipper advertises orders in online freight exchange, reducing empty runs	9 % (350 trucks/ day), Germany	analytical	E
Wittenbrink [123]	long haul transportation, first /last mile transportation	Adherence to a fictitious speed limit of 85 km/h for heavy duty trucks	3 %, Germany	analytical	E
Wygonik and Goodchild [114]	first /last mile transportation	City form and goods movements: evaluation of three possible last mile scenarios (depot-based deliveries, warehouse-based deliveries compared to customers driving to groceries)	Mitigation depends from two to four variables. Road density and distance to warehouse (urban centers or depots) are the main influences. Linear regression equations could be obtained. USA	simulation	A
Yang et al [131]	long haul transportation, first /last mile transportation	Port-integrated logistics system for whole port area of Shenzen: low carbon intense fuels planned, energy monitoring, replacements only by energy-efficient equipment	580,128 t overall, 60 % from transportation, of that 38 % due to ship engines at berth, 2013. Slight mitigation (~1 %) by more efficient electric equipment installed in some areas in 2014, Shenzen, China	case study	e, (f)

contexts [22, 27–30]. A GHG reduction requires a supply of electricity from renewable sources.

Overall, the greatest GHG emission reduction potential is found by the replacement of diesel engines, in two cases by other freight rail transport that operates with electricity and elsewhere by electric trucks. Other fuels are discussed under a vehicle view in frame “E” or within the context of one delivery route in view “C.” Choosing a less carbon-intensive drive concept compared to diesel leads to GHG emission reductions of about 40 % [31–33] while optimistic scenarios see reductions of 73 % [30]. Gonzales-Feliu [31] suggests a traffic strategy for goods delivery within urban areas that could achieve, in its extreme scenario, savings of about 90 % GHG emissions via the aggregation of trips, also addressing the issues of congestion. According to McLeod et al. [34], the consolidation of city deliveries in one operating company (“carry the carrier”) could lead to about 60 % less GHG emissions. A modal shift which leads to less emissions due to a lower energy intensity is considered as an effective measure, with 46 and 55 % GHG emissions reduction potential described by Craig et al. [35] and Jiang et al. [32], respectively.

3.3 Publications on Company Carbon Footprints (Frame B)

The transport company as a logistics network is in the focus of context frame B. Well-known as the “company carbon footprint”, a certain logistics company discloses its overall energy balances and the resulting emissions. These data sets are aggregated; it is not always possible to distinguish energy consumption by source or demand (processes). Both transport and on-site operations are included. This perspective is most commonly taken by sustainability reports, although there are a few case studies and simulations. We will mainly focus on the data provided by the self-reports. These data sets are also aggregated, and it is not always possible to distinguish energy consumption by source or demand (processes). Table 4 lists an overview on the nine publications (three “white” literature sources) in this category, exemplarily including six company self-reports.

The reported data is very suitable to record the overall environmental performance of a single logistics company over time, for example, consecutive years. Due to the system boundary chosen, the data indicate the total effort of all climate protection measures of the company or quantify an overall potential for further improvement measures. This necessarily includes reference values, i. e. explicit information on the extensive variables that caused the GHG emissions. There is no widespread common standard for accounting GHG emissions from logistics activities sustainability reports, thus, the data sets may vary both in reference values and the degree of consolidation, for example, emission data per transportation mode, per scope [17] or per site [36] or various combinations [33]. Deeper insight is not provided by individual processes or sites in the sustainability reports of most companies, but rather GHG emissions for the entire company or the entire group are communicated to the broad public. Since both the sizes of the individual reporting companies and the processes included or international locations of the individual companies vary greatly, it is not possible to compare the published emissions data of the companies based on these values.

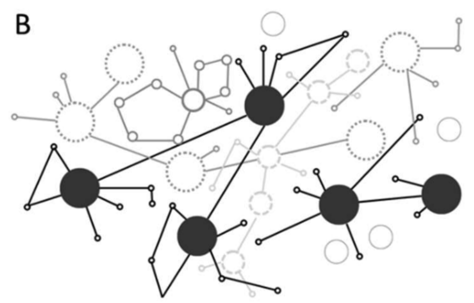
The academic literature considers the strategic level of a logistics company [37, 38] rather than the operational level, while sustainability reports point to both strategic and operational decisions to reduce GHG emissions. This framework focuses only on the logistics company. Neither infrastructure needs nor interactions with other stakeholders within the transport logistics sector are discussed. Mitigation measures that are already implemented within this frame are often amortizing quickly and do not afford structural changes. The best example might be the conversion to LED lighting technology that is mentioned in many sustainability reports [39, 33, 40, 41, 17]. However, within this scope of responsibility, it is entirely possible to change fundamental structures that require a realignment of the logistics network a company uses. [42] studied the motivations of 11 German logistics companies for the adoption of green logistics. They found that all the leaders interviewed favor green logistics but are particularly aiming at achieving the optimum between ecological, i. e. low carbon, and economical performance. The interviews and case studies in [10] showed that the company view is limited by the customers (low prices and short times for logistics services), the subcontractors (level of control and cooperation in terms of commitment to green logistics) and the legislation (requirements, laws and standards). Some carbon mitigation measures include economic advantages. Those are more likely to be actually implemented in the companies.

3.4 Publications on Transport Emissions of One Specific Route of a Logistics Provider (Frame C)

This context perspective most often covers routing optimizations of collection and distribution trips around one or more locations (location routing problem, vehicle routing problem: VRP). Publications in this frame address routing optimization with different constraints (cold chains, time windows, road or customer densities, capacities, speed limits [43]) with different objectives (route-, speed-, emission- or money-optimized). Not all transports that are operated by one company are in focus, but one specific route that is served frequently over time. Table 5 shows the 11 publications in this category. All of them are scientific publications.

A lot of the recently published literature uses this background frame, even though those publications are not necessarily mentioned in this analysis due to the lack of specific absolute values. It addresses, in its basic type, the question in which order customers have

Table 4: Analyses of publications on company carbon footprints (context frame B).
The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework:
f: fuel intensity, e: energy intensity, a: activity.

<table>
<tr><td colspan="2"> </td><td colspan="4">Company Carbon Footprint
9 Publications</td></tr>
<tr><th>Authors</th><th>Logistic activities in focus</th><th>Context</th><th>Quantitative Data on energy consumption or GHG emission mitigations</th><th>Method</th><th>IPCC factor</th></tr>
<tr><td>Alpensped Internationale Logistik [16]</td><td>Network design, long haul transportation</td><td>Efficient logistics concepts (distribution centers), shipment bundling, fleet modernization</td><td>No mitigations, status quo: Corporate Carbon Footprint: 17,527 t CO_2e, Transport Carbon Footprint: 276.3 kg CO_2e/ item, 2017 -48.7 % compared to 2016, Germany</td><td>Case study (report)</td><td>e</td></tr>
<tr><td>Kellner [18]</td><td>long haul transportation, first /last mile transportation</td><td>Impact of regular road traffic congestion on the GHG emissions of a real-world distribution network, variable number of distribution centers</td><td>Congestion has an influence of 2.5 % on the total GHG emissions of a food retail network, Austria</td><td>simulation</td><td>e</td></tr>
<tr><td>Zagler and Debes [33]</td><td>network design, long haul transportation</td><td>Hub-and-spoke network, consolidation, eco-driving, bio-diesel, only EURO VI/VIc trucks, tire and air filter monitoring, planned speed limit (84 km/h)</td><td>8,729,679 kWh/a for heating, 7208,863 kWh/a electricity (site specific values available), 199.8 gCO_2e/km (TTW), 8,447,530 kg CO_2e/a from fuels, Germany</td><td>Case study (report)</td><td>a, f, e</td></tr>
</table>

Hacardiaux and Tancrez [37]	network design, long haul transportation	Horizontal cooperation, location inventory problem; parameters vehicles capacity, facility opening cost, inventory holding cost, order cost, demand variability and distances; low opening and order costs lead to lower GHG values through cooperation	16 % per average, Belgium	simulation	a, (e)
Munoz-Villamizar et al [38]	routing, first /last mile transportation	VRP optimization with constraints: time windows, legislative, considering emissions of “non value-adding activities” for real-world effects (routing errors)	Bigger van capacity and change in routing strategy (from low lead time to low costs): from 50 kg CO_2e to 40 kg CO_2e; 8 h operation time, Bogotá, Colombia	case study	a
Clausen [39]	mainly long haul transportation	Various improvements	No mitigations, status quo: 0.035 kgCO_2e/tkm on average (values per country: 0.026 – 0.042 kgCO_2e/tkm), Denmark	case study (report)	a, e, f
Mendouga [40]	buildings services, training	LED lighting, Photovoltaic plant, eco training	From 2,258,971 kWh/a (2013) to 1,437,838 kwh/a (-36 %), Germany, 2016	case study (report)	e
Koch [41]	buildings services, training	Eco driving, LED lighting	18,035 l/ 1.3 % / 62.8 t CO_2 / 13 g CO_2/km less than 2017 for 75 Scania trucks; 9,264 l/1.2 %/ 23.3 t CO_2 / 8.52 g CO_2/km less for 26 Mercedes trucks; electricity for buildings 2,237,231 kWh/a, 2018, Germany	case study (report)	e
Zhang et al [121]	first /last mile transportation	E-commerce delivery company with diesel vans: outsourcing of parcels to public transportation via willing bus passengers under congestion	17 % less traveled distances and emissions, Singapore	simulation	a

Table 5: Analyses of publications on transport emissions of one specific route of a logistics provider (context frame C). The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework: f: fuel intensity, e: energy intensity, a: activity.

<table>
<tr><td colspan="2"> </td><td colspan="4">One route of a logistics provider
11 Publications</td></tr>
<tr><td>Authors</td><td>Logistic activities in focus</td><td>Context</td><td>Quantitative Data on energy consumption or GHG emission mitigations</td><td>Method</td><td>IPCC factor</td></tr>
<tr><td>Bergmann et al [61]</td><td>routing, first /last mile transportation</td><td>Route optimization for integrated first and last mile activities, constrained by capacity and precedence</td><td>16 %, in Bengaluru, India</td><td>simulation</td><td>a</td></tr>
<tr><td>Büttgen et al [60]</td><td>network design, first /last mile transportation</td><td>E-vans and e-cargo bikes with depot (two-stage) instead of diesel vans without depot for parcel delivery in Innsbruck</td><td>96 %, in Innsbruck, Austria</td><td>simulation</td><td>f, (a, e)</td></tr>
<tr><td>Cai et al [55]</td><td>routing, first /last mile transportation</td><td>Carbon minimization-oriented VRP considering time-varying speed for automated connected vehicles, flexible departure times and waiting times</td><td>12 % compared to classical VRP distance minimization, China</td><td>simulation</td><td>e</td></tr>
<tr><td>Croci et al [56]</td><td>first /last mile transportation</td><td>Replace diesel delivery vans with e-vans, activity parameters remain unchanged, LCA on last mile</td><td>37 % in Turin and 49 % in Milan, Italy (avoided daily GHG emissions: 121/167 kg CO_2e)</td><td>simulation</td><td>f</td></tr>
<tr><td>Duarte et al [58]</td><td>first /last mile transportation</td><td>Replace diesel with electric engines for urban service vehicles</td><td>57 % less energy consumption, in Lisbon, Portugal (WTW)</td><td>case study</td><td>f</td></tr>
</table>

Figliozzi [43]	network design, first /last mile transportation	Analysis of the dependencies of travel distance/ time/emissions and depot location, time window, customer instances, congestion and speed limits	Depending on parameters, both positive and negative values, USA	analytical	a, e
Rahman et al [53]	routing, long haul transportation, cold chain	Vehicle routing problem for a single round trip and various split routes, including in-field refrigeration, fuel consumption and inventory holding emissions, only CO_2	13 % for a single round trip compared to the better of two split routes, including holding emissions of refrigerated warehouse, in Bangladesh, India	simulation	a, (e)
Lammert et al [59]	long haul transportation	Fuel consumption of two platooned tractor-trailer combinations compared to their standalone consumption	3.7 to 6.4 % fuel savings, best setting 55 mph, 30 feet following distance, and 650,00 lbs gross vehicle weight, USA	case study	E
Lin et al [52]	network design	Urban consolidation centers	Depending on scenario, up to ~50 % energy savings/GHG emissions possible, China	simulation	a
Koc et al [27]	network design, first /last mile transportation	Changes in depot location/ fleet composition according to customers' locations in speed limited zones	Depends on parameter settings, Canada	analytical	a, e
Temporelli et al [62]	first /last mile transportation	Replace diesel vans with e-vans or e-cargo bikes for city deliveries, activity parameters remain unchanged, LCA with functional unit of vehicle km traveled	0.173 g CO_2e/km / 52 % less (e-van) & 0.250 g CO_2e/km / 76 % less (e-cargo bike), (diesel van: 0.331 g CO_2e/km; e-van: 0.158 g CO_2e/km; e-cargo bike: 0.079 g CO_2e/km), Italy	case study	f

to be served to achieve an optimum in terms of route lengths, as described first by [44]. The optimization models describe functional dependencies rather than calculate a single solution for a specific constellation, therefore, specific values of GHG emissions are not always mentioned. Nevertheless, mathematical and meta heuristic modeling of deliveries that propose a solution of a (sub)type of the VRP problem under at least one aspect of lowering GHG emissions is a topic that receives high interest [45–51]. Using these algorithms for the routing optimization of long-haul deliveries has not yet been focused on as all of the publications found within this cluster relate to urban areas. The GHG emissions of one or multiple locations are usually not considered [52], although there are exceptions that use rather coarsely estimated values [53] and they appear within the economic costs modeling [54]. Instead of the energy consumption within the site, its actual place, the location of the site, is of importance to optimize the routes considered (location routing problem) [27, 43]. A large part of sources that take this perspective report simulated data from optimization modelling. In addition to the overall fuel consumption of the route, the optimized parameters for the number of vehicles, leaving times, order of customers, location of depots or charging stations are presented. Additionally, the model itself is in focus [55]. Calculation times and algorithm efficiencies are reported and compared to different approaches.

Fuel consumption data for road transports are almost always taken from model databases (e.g. HBEFA (for TREMOD or ecoInvent data base), [56], [57], or MOVES (e.g. for GREET)), [43], or from the truck/van manufacturers [53]. Duarte et al. [58] and Lammert et al. [59] use their own logged data in their case studies. In the case of vehicles with a small capacity below 3.5 t that are often found in the urban contexts, fuel consumption is often estimated by a driving-related approach (in l/km), [60], [61]. Because the payload variation does not exceed 2 tons, it is not necessary to use the performance-related index tonne kilometers. The operating level of transport companies is well represented by the part of scientific literature concerned with routing (5 out of 11). But it should be mentioned that this is limited to the consideration of one route within the portfolio of a company and that all companies studied operate within urban deliveries.

The distance traveled is the main influence factor on GHG emissions within the route view, thus, the proposed mitigation measures include distance minimization by optimal routing [52, 53, 43, 55, 61], and a reduction of the fuel carbon intensity by choosing electric vehicles [60, 56, 58, 62].

3.5 Publications on Product Carbon Footprints along the Supply Chain (Frame D)

This category includes publications on transport-related emissions of one specific good from cradle to grave. The delivery chain view of one specific good or product group often appears within the context of the modal shift. Parts of the chain are substituted by other modes of transport, means of transport or distribution routes. In addition, all publications that studied the GHG emission of supply chains (SCs) are subsumed here. The 10 publications in this category, mostly (9) peer-reviewed scientific articles, are listed in Table 6.

The reference value is often a defined quantity of a specific product. In some cases, energy and GHG accounting include all legs of the transportation. Others refer to a wider scope, including production and selling processes. There are some literature reviews published recently that focus on the production perspective of transports, for example, [63].

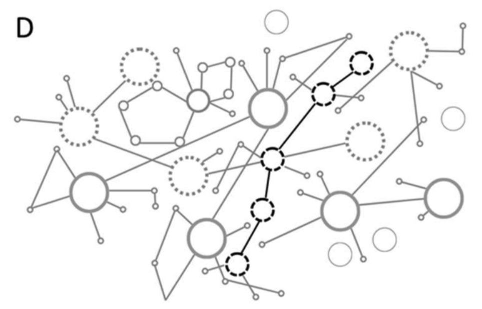
Logistics play a minor role in energy/emission accounting within the SC view, usually about 5 %, and is treated with a higher data aggregation level or coarser modeling of transport [64, 65]. When assessed from a production view, measures for GHG emission reduction comprise packaging and logistics-oriented product design.

Rizet et al. [66] quantitatively discuss the energy consumption and GHG outputs of transport along the SCs for different goods ending up in different countries. The total length of the trips, including consumer's trips, and the carbon intensity of the electricity mix make the biggest differences. Other effects, such as the amount of product sold per time and area unit, are studied. Unlike other publications (i.e. [35, 67, 68, 65, 69]), Rizet et al. include last mile logistics.

The measure that is mentioned most within the literature reviewed is network design regarding lower GHG emissions. It is difficult to quantify those potentials because of different scopes considered for the accounting. As long as the distances traveled overall remain within the same magnitude, an optimization via depot relocating or optimal number of transshipment centers could lead to 2 % [67], 3.5 % [68] or 13 % [70] THG emission reduction. All other proposals of different network constellations refer to the relocation of individual SC sections (e.g. sourcing or production) to substantially different regions [64], so that in addition to the transport routes [66], the energy consumption characteristics of all SC processes also change [69]. The specific numerical values within the papers mentioned refer to the overall SC GHG emission assessment and are not limited to the share caused by logistics processes.

Choosing a different mode of transport can lower the GHG emission significantly; Craig et al. [35], although predominantly assigned to frame A, cite 46 % less emissions when using a freight train network along whole SCs; McKinnon and Piecyk [71] propose end customers taking a city bus for buying all items within one trip. These efficiency effects through higher consolidation levels lead to higher GHG savings within logistics than restructuring networks as long as the transport routes are not drastically shortened.

Table 6: Analyses of publications on product carbon footprints along the supply chain (SC; context frame D). The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework: f: fuel intensity, e: energy intensity, a: activity.



Supply Chain View
10 Publications

Authors	Logistic activities in focus	Context	Quantitative Data on energy consumption or GHG emission mitigations	Method	IPCC factor
Rizet et al [66]	first /last mile transportation, cold chain	Comparison of different SCs for apples, yoghurt, jeans and furniture in Belgium, France and UK	Various effects are explained, no mitigation. The total trips lengths, including consumer's trips, and the carbon intensity of the electricity mix make up for the biggest differences. Other effects as the amount of product sold per time and area unit are studied.	simulation	a, f, e
Daryanto and Wee [67]	network design	Integrated emissions aware of decision-making along SC of manufacturer, 3PL and buyer instead of single decision-making	2.1 % (from 279 to 276 t CO_2e/a), Indonesia	simulation	a
Igl and Kellner [68]	network design	Order rhythm procedure, network structure for fewer truck kilometers: limits for direct traffic, higher minimum order quantity, time bundling, one-time weekly delivery	Direct transports limited to more than 11 t: 3.49 %, Germany	simulation	a, e

Kannegiesser et al [65]	production, network design, long haul transportation	Trade-offs between totals costs and GHG emissions along automotive SCs, worldwide data	Trade-off between costs and emissions: -30 % emissions for +8 % costs; highest emissions from production phase, transports ~ 5 %	simulation	-
Sundarakani et al [69]	production, network design, long haul transportation	Modeling of total emissions and energy consumption along four-stage SC	Status quo: Consumption of 0.437 kWh for logistics (1,493 kWh in total) per product, East Asia	simulation	-
Sirilertsuwan et al [64]	production, network design, long haul transportation	Three-stage-SC optimization for different targets (cost, emissions, or both) and markets including processes to support and control sustainability, worldwide data	Mitigation possible by optimal SC configuration. Depending on location of fiber, fabric and garment production, between 6,000 and 160,00 kg CO_2e/batch of 1,800 viscose T-Shirts	simulation	f, a
Kellner and Igl [70]	network design, long haul transportation	Many-to-many network constellation instead of hub-and-spoke network	2.1 to 13.5 %, Germany	simulation	a
McKinnon and Piecyk [71]	first/ last mile transportation	Last link of SC: last mile, comparing home deliveries to customers trips for small items	Depends. Range from 8.55 to 0.32 gCO_2/item, UK	analytical	a, e
Dong and Miller [122]	long haul transportation, first/ last mile transportation, cold chain	Different cold chains of four agricultural product groups were studied with regards to energy and emissions accounting cradle-to-grave	No mitigation. In four vegetable/fruit scenarios, most of the emissions (54 % on av.) arise from cold chain activities. For vegetables at 2°: 0.58 kg CO_2e/kg consumption, China	simulation	-
Schrampf and Hartmann [7]	long haul transportation, first/ last mile transportation	Five exemplary Austrian SCs	Status quo: energy consumption for – road salt 20 kWh/ pallet; – toilet paper 120 kWh/ pallet; – trade average movers 135 kWh/pallet; trade slow movers 90 kWh/pallet; spare parts 335 kWh/ pallet; 0.01 (ship) – 1.25 (van) kWh/ pallet*km, Austria	analytical	-

3.6 Publications on Vehicle-related Emissions (Frame E)

This context frame sums measures concerning the road freight vehicles leading to lower energy consumption and emissions, regardless of a specific logistics activity. In this category, 11 publications (7 "gray" reports) are shown in Table 7.

While most of the publications cite a variety of parameters for considering the actual configuration of the logistics network, some papers include information on potential reductions in energy consumption or GHG emissions without using logistics activity data [22], [72]. These are grouped under the perspective "E", the vehicle view.

Within this review, the measures concerning a freight vehicle's sustainability can only be touched exemplarily. Research is mostly focused on automotive engineering, and the aspects related to the logistics activities are only considered secondarily or left out. The resulting publications taking this perspective could not be found in the primary search but by additional searches with different search terms. Fuels for heavy duty vehicles are also in the focus of studies; both energetic comparisons referring to the use phase of the fuels and full life cycle analyses over all phases, including production and distribution, can be found. The two publications mentioned under section "E" for assessing fuel or electricity for drive trains [73], [74] take a "well-to-wheel (WTW)" approach, combining scope 1 ("tank-to-wheel" TTW) and scope 2 ("well-to-tank" WTT) emissions as recommended by the standard EN ISO 16358 [75].

There are a number of measures which, regardless of the actual logistical use of a vehicle, can be expected to reduce energy consumption and emissions in any case. The numerical values in the literature can provide

Table 7: Analyses of publications on vehicle related emissions (context frame E). The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework: f: fuel intensity, e: energy intensity, a: activity.

<table>
<tr><td colspan="2">
</td><td colspan="4">Vehicle View
11 Publications</td></tr>
<tr><th>Authors</th><th>Logistic activities in focus</th><th>Context</th><th>Quantitative Data on energy consumption or GHG emission mitigations</th><th>Method</th><th>IPCC factor</th></tr>
<tr><td>Peiro Frasquet and Indinger [72]</td><td>long haul transportation</td><td>Aerodynamical optimization of a generic articulated truck/trailer-truck combination</td><td>4.53/7 % less energy consumption for empty vehicle, Germany</td><td>simulation</td><td>e</td></tr>
<tr><td>Bidart et al [73]</td><td>does not apply</td><td>WTW LCA for biomethane from biogas as a fuel via two production routes</td><td>0.28 to 0.72 kg CO_2e/m^3 via biogas upgrading (0.36 to 1.04 kg CO_2e/m^3 via catalytic methanation)
WTW: 0.03 to 0.07 kg CO_2e/tkm for biomethane, for natural gas & diesel: 0.16 to 0.18 kg CO_2e/tkm & 0.17 to 0.19 kg CO_2e/tkm, Germany</td><td>simulation</td><td>f</td></tr>
</table>

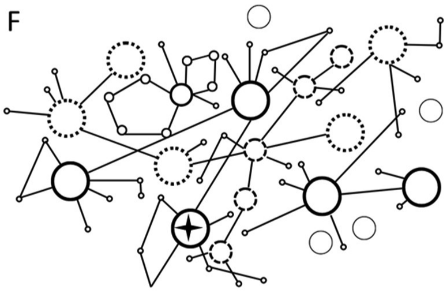
Unterlohner [74]	long haul transportation	IVECO truck fueled with fossil LNG instead of conventional diesel; case study with driving test cycles	7.5 to 7.9% compared to the tested diesel truck with GWP100; -13.4 % resp. -13.6 % with GWP20, Austria	case study	f
Delgado et al [77]	mainly long haul transportation	Long-term technology improvement package: reduced aerodynamic drag coefficients, reduced curb weight, energy recuperation, improved brakes and tires, hybrid powertrain, potential study	Up to 43 % for city driving, 34 % for long haul, from 2030, Europe	analytical	e
Lohre et al [78]	long haul transportation	All tires replaced by low rolling resistance tires	~ 5 %, Germany	Case study	e
Deschle et al [125]	long haul transportation	Avoid one stop at a signalized intersection, gross vehicle weight ~ 35 t, experimental case study on measured data	0.32 kg less CO_2; Emission savings within 2 km in g CO_2e for: no-stop: 1461(24 %); slow down: 1588 (17 %); stop: 1912. The Netherlands	case study	e
McKinnon [124]	long haul transportation	Lower maximum truck speed	Depending on fleet size / speed limits, up to 27 %, UK	simulation	e
Wietschel et al [76]	Does not apply	Comparison of GHG emission over the life cycle of trucks for different fuels	For the life cycle of one truck: diesel fueled: ~ 50 t CO_2e, synthetic methane fueled ~ 150 t CO_2e (200 % more), methane from renewable resources ~25 t CO_2e (50 % less), Germany	analytical	f
Wittenbrink [117] Lohre et al [78] McKinnon [97]	training	Annual instruction and training of driving personnel in fuel-efficient driving, only heavy trucks	5 %, Germany 8 to 10 %, UK	case study	e

an orientation to the expected order of magnitude in the context of the application in logistics. The use of biomethane as a fuel holds, with about 50 to 80 % less GHG emissions compared to diesel fuel, the greatest potential as a single measure [73, 76], followed by eco driving training (about 10 %). All measures that lead to a smoother traffic flow with reduced braking and acceleration processes reach the same level. Since the effect of aerodynamic improvement measures is dependent on vehicles driving dynamics and environment, the numerical values given in [72] and [77] are roughly 3 to 7 % and 5 to 10 % reduction potential, relatively; a real-life example case in [78] reports an average 10 % reduction in diesel consumption. Delgado et al. [77] calculate a technological potential of several mixed technology improvements of up to 42 % fuel reduction until 2030 which refers to an urban driving cycle. For long hauls, the aerodynamical and tire improvements are the most effective measures found within this potential study. Holmberg et al. [79] calculate a 7.4 % reduction in diesel consumption for each 10 % friction reduction in trailer-truck combinations. These reductions could be achieved by, for example, low friction coatings on the component level.

3.7 Publications on Energy Consumption and Emissions of Single Logistics Sites (Frame F)

Context frame F refers to the process level of a site and focuses on individual activities in the areas of infrastructure transportation, warehousing, storage, or goods handling. In addition, publications that provide quantitative data on energy consumption and GHG emissions of entire logistics sites, as opposed to transportation, are included. Fifteen publications are listed in this category (Table 8). The proportion of "gray" literature (9 out of 15) is high. Most of the "F" publications are case studies.

Table 8: Analyses of publications on energy consumption and emissions of single logistics sites (context frame F). The abbreviations f, e and a refer to the possible reduction approach according to the IPCC framework: f: fuel intensity, e: energy intensity, a: activity.

<table>
<tr><td colspan="2"> </td><td colspan="4">Logistics Site View
15 Publications</td></tr>
<tr><th>Authors</th><th>Logistic activities in focus</th><th>Context</th><th>Quantitative Data on energy consumption or GHG emission mitigations</th><th>Method</th><th>IPCC factor</th></tr>
<tr><td>Rüdiger et al [81]</td><td>all storage-related activities</td><td>Handling warehouse for palletized goods (whole site)</td><td>Of 482,340 kgCO$_2$e/a: 50 % intralogistics, 41 % other electricity, 9 % geothermal heating, Germany</td><td>case study</td><td>-</td></tr>
<tr><td>Fichtinger et al [23]</td><td>warehouse management</td><td>Combine inventory and warehouse management for optimized area sizes, stock levels, handling times/ frequencies and, thus, lowest overall energy consumption: 3 warehouse layouts and 3 sourcing strategies</td><td>Eastern Europe / local supply: saving from 5 to 15 % compared to Far East (where high safety stock levels are needed)</td><td>simulation</td><td>a, e</td></tr>
</table>

Hauth [19]	buildings services	Zoning of the warehouse (heated/lighted or cold/dark) according to personnel deployment	64 % (from 11,230 to 4,076 kWh/a), Germany	simulation	A
Siegel et al [20]	intralogistics	Warehouse strategy: control of stacker cranes – adaptation of travel time to throughput (instead of standstill), parameter study	Up to 37/17 % at 50/80 % capacity utilization, Germany	case study	e
Perotti et al [3]	all site-related logistics activities	Build up total GHG emissions and energy consumption of a site via emission intensity values for core process categories, without road transports	Status quo of 11 sites (8,000 to 140,000 m^2 floorspace) for model validation, GHG from electricity, fuels and refrigerants ranging from 6 to 1,551 t CO_2e/a, Italy	simulation	-
Süssenguth and Wolfensteller [6]	all storage-related activities	On-site energy demands of six warehouses, thereof 2/3 for heating on average	100 kWh/$m^2 \cdot a$ for warehouses on average (ca. 60 to 130 kWh/$m^2 \cdot a$), 2008, Germany	case study	-
	intralogistics	Intralogistics: conveyor plants Frequency converter, speed control (motor efficiency), low friction losses, design adapted to average load instead of full load, energy recovery	From 993,750 to 487,500 kWh/a: ~50 % savings, Germany		e
Meneghetti and Monti [82]	cold chain	Cooling energy, 22,459.5 m^3, cold storage (23 °C/Northern Italy), six floors	624,506 kWh/a (27.81 kWh/($m^3 \cdot a$)); 23,862 kg CO_2e, Italy	case study	n. a.
	buildings service	Lighting, 1,449 m^2 floor space, cold store, six floors	62,748 kWh/a (43.30 kWh/($m^2 \cdot a$)), Italy	case study	n. a.
	intralogistics	Storage and retrieval, high rack with crane and satellite SRBG, six floors	43,283 kWh/a, Italy	case study	n. a.

Bachmair [83]	intralogistics	Unloading truck with electric forklift truck (one truck load takes one hour)	7 kW · 8 h/d · 251 d/a = 14,056 kWh/a, Austria	case study	n. a.
	intralogistics	High bay warehouse, 30 pallets per hour, 8 h, 251 days	15 kW · 8 h/d · 251 d/a = 30,120 kWh/a, Austria	case study	n. a.
	intralogistics	Reach truck or forklift, 1 m height, 600 kg weight (one lift)	20,000 J, Austria	case study	n. a.
Lampe [84]	all site-related logistics activities	One whole site of contract logistics: warehousing and picking of vehicle parts, energy consumption mainly by automated small parts warehouse	390,000 kg CO_2e (2016), 0.98 kg CO_2e per custom assembled item, Germany	case study	
Freis et al. [86]	all storage-related activities	Build-up of an energy model of three types of warehouses; parameter variations on energy efficient design options for building skin, building technologies (services) and intra logistics processes, calculation of total GHG emissions for the three generic types	Status quo of energy distribution: Building technology at 17 °C: 80 % of GHG emissions for manual warehouse, ~34 % for semiautomated logistics center; ~11 % for automated distribution center, Germany	case study	e
	intralogistics	energy recovery units in miniload cranes for high racks	35 % less crane energy; about 16 % less GHG emission for automated warehouses, Germany	case study	e
	buildings service	Motion control for lighting in manual warehouse, parameter study	6 % less GHG emissions in total, lower heat losses and higher external heat energy consumption included. 13 % CO_2e savings for manual chilled warehouses, Germany	case study	a

Zhao et al [94]	intralogistics	Drive of unit load conveyors: 100 conveyors, two-shift operation, 6-day week	27,000 kWh/a (small) – 73 000 kWh/a (big) savings 14 - 38 t CO_2e per year, China	analytical	e
Dobers et al [132]	warehouse design	Optimize design input variables for warehouse (velocity profile of vehicles and warehouse shape) for lowest operation cost and energy consumption	Depends on constellation; compare to optimal solutions possible, Germany	simulation	e
Zadek et al [127]	intralogistics	drive concept for forklifts Comparison between diesel, battery, fuel cell/ natural gas and fuel cell/solar H2 operation	40 % from battery to fuel cell/natural gas (6,541 t CO_2e/a resp. 16,021 t CO_2e/a less from battery to fuel cell/solar H2), Germany	analytical	f
Díaz-Ramirez et al [105]	Intralogistics, warehouse management	Packaging/ scheduling with two parallel machines and a dominant job: reducing waiting times	Depends on constellation, Colombia	simulation	e
Dobers et al [102]	all site-related logistics activities	Build up total GHG emissions and energy consumption of a site via emission intensity values for core process categories, without road transports, worldwide data	ambient storage sites 0.49 to 57.94 kg CO_2e/t For storage with order picking: measures to reduce the electricity consumption of storage equipment by 25 % – from 16.01 to 14.97 kg CO_2e/t, Germany	simulation	-

Although most of the energy consumed within the logistics sector is used for transportation, consumption also takes place at the logistics sites. Together with the company view “B” and the SC view “D”, this view considers the consumption of materials and waste [3] as it occurs within the buildings, mostly due to packaging processes. Several publications (e. g. [2, 3]) cite Doherty and Hoyle [4] for the share of 11 % that warehouses roughly contribute to the GHG emissions of the logistics sector, Ege et al. [80] used European Energy Agency data for a share of 13 %, while Süssenguth and Wolfensteller [6] cite 25 % from a German study based in 2008. A SC model for Austria [7] calculates shares between 10 and 25 % for all non-transport-related energy consumption.

There seems to be a consensus that the amount of emissions is closely linked to the activities and value-added services offered by the warehouses [81]. When analyzing a specific process or activity of a logistics site, the reference value is often a period of time [82, 83] or an area, especially for building services such as lighting or heating. Lampe [84] recognizes the area of a site as a reference that is not sufficiently informative and suggests instead a reference to handled or finished goods to take into account the huge possible range of value-added services provided by logistics companies.

The authors, who consider complete logistics sites, group all energy-consuming processes within a warehouse into clusters. These are often similar: air conditioning and heating, lighting, mobile material handling with equipment such as forklifts, fixed storage and retrieval with equipment such as automated high-bay racks or conveyor belts. Dobers et al. [85] together with Perotti et al. [3] propose a "service view" as a reference value for the energy consumption. Goods might be stored, stored at a controlled temperature, transshipped, picked (i. e. commissioned), sorted and/or handled additionally (e. g. packed or mounted). The energy consumption should refer to the partial quantities of goods that undergo the same services, resulting in a set of performance indices. The share of the process clusters may vary, especially when comparing them in literature over a longer time period. Süssenguth and Wolfensteller [6] cite, for an average value of 100 kWh/m²*a, a share of two-thirds for heating energy. The electricity consuming process clusters of lighting, goods handling with mobile floor bound equipment, and goods handling with immobile equipment use roughly equal parts of the remaining share (one-third). In a more recent study, Freis et al. [86] found that the energy distribution in logistics buildings is nonuniform and depends strongly on the degree of automation. They calculated a share below 25 % for intralogistics equipment in manual warehouses, but around 90 % in automated distribution centers. But again, having considered mostly default values derived from industrial standards or activity estimations, they point out that those shares, as well as the absolute values, depend on the actual activity profile of a warehouse. They concluded that a GHG neutral operation is possible for a manual warehouse with its own photovoltaic electricity supply [86]. Applying the optimized design options for the automated and semiautomated reference buildings, GHG emission could be reduced to 8 % of the base scenario.

There are also many proposals to reduce energy consumption and GHG emissions due to the high variance in processes that take place at the various specialized logistics sites; however, numerical values are not always given (e. g. [80]). Furthermore, there are various degrees of automatization. As a result, the energy demand is distributed differently among the various process groups [87, 86, 82], making it difficult to evaluate which GHG mitigation measure will perform best in most of all possible site constellations. The efficiency measures found within the literature can be grouped according to the processes in which the energy is needed, and supplemented by measures to lower the carbon intensity of the energy used. A simplified framework for the influences on energy demands and resulting GHG emissions in logistics sites can be derived from [87, 86, 85, 81, 88–91, 3] (see also Fig. 3). Possible measures are:

– Influence of zoning on energy consumption: set up zones without lighting or room heating/cooling. This is applicable in fully automated zones of a building and best considered within the planning phase of a building. Savings of 13 % [86] and 34 % [19] GHG emission are reported.
– Active management of storage and retrieval [92]. There are strategies that minimize distances traveled, retrieval times or energy [93]; thereof, the energy-centered approaches need slightly less energy than the distance-based ones.
– Consideration of building form and constellation [87, 86], especially for deep freezing warehouses [82], within the planning phase for minimizing cooling demands; consider the insulation effect of building materials, for example, green roofs.
– Energy-efficient design of conveyor systems, better adaptation of the drive to variable loads [94].
– Energy-efficient strategies for the handling of materials by conveyor plants could be reducing maximum speeds, choosing a workspace layout that minimizes distances, adapting driving speeds to workload and allowing for energy recuperation [86, 94].
– Review of different building services regarding energy efficiency.
– More involvement of renewable energy sources for on-site energy supply, including truck services, for example, trailer cooling (electricity during the loading/unloading processes).

4 DISCUSSION

4.1 Data Sources and Methods Applied within Reviewed Publications

The data sets reported in literature which were evaluated in this review have different backgrounds. The largest group (48) is made up of peer-reviewed publications, followed by 24 reports of research projects or articles in journals, supplemented by 6 sustainability reports. Several geographical backgrounds, mostly throughout Europe, Asia and the Americas, are covered. Publication periods vary from 2003 to 2022 due to essays added during the backward search, data may refer to slightly earlier periods. There are different methods applied to gain insight into energy or GHG emissions accounting in the context of logistics. Scientific publications use mainly two methods to describe the energy consumption or GHG emissions of logistics companies or sites: a simulation or modeling, often based on generic data, or a case study.

A statistical representation is often used to describe an extensive set of data more clearly or reveal certain patterns in this set of data. The huge diversity of logistics companies or sites and their inhomogeneous starting situation makes it difficult to reflect energy consumption by statistical analyses. The decisive reason not to use a statistical description here might be that the sample size required would be too large due to the high fluctuations to be expected. The sample would have to originate from the same population, i. e. spatially, temporally and methodologically comparable data sets, if it is to reflect the situation of current logistics sites correctly. However, complete data sets are not yet available on a sufficient scale and the expected scatter of the values is too high for a condensed statement to be applicable by statistics. Many of the papers deal with problems that can only be analyzed by considering the system dynamics, which require simulation models. An example is the optimization of a logistical network. Another important reason is the confidentiality of the data. In order to summarize the operational data of several similar companies in a scientific statistical study, data would have to be taken from these companies that are comparable in some way. This could already be outside the consent of the logistics companies, which could, thus, reveal important operating procedures that could be part of the unique selling proposition of their service, or see their negotiating position weakened towards customers by the disclosure of their energy consumption data or costs.

Research on energy consumption based on the logistic activity of the vehicle fleet rarely uses experimental data such as measurement data which the companies have collected themselves. Unlike passenger cars, commercial vehicles can have a very wide range of variants [95, 72]. There are significantly more different chassis configurations represented on the market, in addition to the degrees of freedom in bodywork and trailers. If one also considers that the trucks of external companies are also used at many logistics locations, it is understandable that the energy consumption for providing a certain service will not be a single value, but a range. With the goal of GHG emission reductions in the logistics sector, we are primarily interested in data over a longer period of time and a larger area (i. e. for all routes leaving the site) than in data referring to a single trip. Modelled data that summarizes the energy consumption of all models and possible variants assigned to a particular truck class is sufficiently accurate because for our scope of interest, it is most likely that many different trucks will perform the service. If the energy consumption of a single trip is focused on, the driver has a great influence [96, 97].

4.2 System Boundaries Applied within Reviewed Publications

As shown in several studies, there is a strong dependence on energy saving and logistics activity, such as network or fleet constellation [70], due to constraints, for example, maximum vehicle capacity [52], time windows, customer demand or depot location [31], [27], to mention just a few. These constraints lead to non-monotonic correlations between changes in input parameters and the emissions that depend on them [98, 52, 99], and they rely on many possible influencing parameters and constraints. Therefore, it is necessary to differentiate between the specific “logistics” scenarios in which the proposed vehicle-related mitigation measures are applied. It is important for measurements aiming at fuel exchange to include the upstream chain emissions of fuels (Well-to-Tank) and, if applicable, vehicle power train components, especially when comparing emissions in an international context.

Publications focusing on electricity demand – for on-site processes and vehicles throughout – choose scope 2 as a GHG emission reference frame. If fuel consumption is in focus, many publications use simplified estimates of distance-related TTW consumption that only refer to scope 1 emissions. This is adequate if there are no alternative vehicles, fuels or infrastructures within the scopes of comparison and only the reductions in GHG outputs are in focus, not their absolute values. The full LCA of a fuel, consisting of all WTW emissions, is found in [76, 100, 101]. This is in accordance with the standard EN 16258 methodology for the calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) [13]. The wider frame of a vehicle for an LCA is taken in [100] and [99], but only batteries are considered. This is in accordance with the “environmental footprint calculator” tool of a truck manufacturer [101]. To date, there are no LCA data sets available for all vehicle components that are uniquely designed for a specific driving technology. However, their GHG emissions are estimated to remain within the same range as before. Perotti et al. [3], modelling the processes within logistics sites comparable to the publication of Bouchery et al. [102], also consider the buildings and materials flows, thus, suggesting an LCA for a logistics site. The approach of a full LCA for logistics services is also present in [62, 56]. Scope 3 emissions are consistently left out.

Study results with different geographic backgrounds are rarely transferable. The energy sectors of individual countries can be very differently positioned, thus, resulting in different emission factors, and there are also country-specific constraints in the operational logistics business. Hao et al. [103], for example, report average load factors of Chinese lorries around 140 %. Differing from the status quo in the European Union, Holden et al. [104] find a great reduction potential in limiting the fuel consumption of trucks per kilometer in South Korea because there has not yet been any regulative directive. Another 2012 dated study mentions the “high carbon content of UK electricity” [66]. East Asian papers sometimes refer to “deterioration costs and emissions” or similar penalties imposed for the damage of goods, especially in cold chains, during the delivery [67, 105]. These issues are not discussed in European studies. Dobers et al in [85] provide a good example of aggregating global data, where the GHG emissions for ambient storage sites range from 0.49 to 57.94 kg CO_2e/t.

4.3 Influence of Context Frames

The context frames proposed were well appropriated for clustering the literature portfolio. It is obvious that each particular context view, which corresponds to a certain focus of the respective research, requires its own input data sets and acquisition methods. Macroscopic views over areas need macroeconomic data sets, broad time horizons and averaged respective agglomerated data that include the different logistics operators serving the area of interest. A company perspective will focus on the overall performance of all subsidiaries, and the interactions between sites, locations and resources, but it seems unlikely that consumptions of upstream activities will be discussed within this frame. Both generic and self-collected data can appear. Regarding GHG mitigation measures, the focus will lay on measures with both ecological and economic benefits. The route view, frame C, explores mostly the optimal supply of a specific customer quantity, and, therefore, requires the highest spatial resolution. Input data can be averaged over longer times, but it is not unusual to consider specific vehicle models instead of generic categories. Upstream activities are of interest within the supply chain view that will cover the restructuring of logistical networks, including the modal shift to rail transport. Besides road transport, rail and oversea shipping is often included within this view that considers the longest transport distances of all context frames. Because the accounting of transportation is only one of several chain links, input data is needed in a coarser estimation. If the object of interest is a heavy duty vehicle, the life cycle approach includes the production phase, the use phase and the disposal, which allows for an unbiased impact assessment even in the case of a technology exchange. The assessment of the fuel consumption within the use phase of a vehicle needs the well-to-tank pre-chain emissions data as well as the distance-specific fuel consumption in fine resolution, allowing for the variation of influencing parameters, such as load weight, velocity or road gradients. The same fine resolution is needed when site-related activities are in focus. The GHG emissions from the logistics sites are clearly lower than the GHG emissions of the corresponding transports, and are often studied separately. Within this context, data sets from the process level are cited.

4.4 Quantitative Data on Energy Consumption and GHG Emissions

Due to the cross-sectional tasks of logistics, there are many different views of logistics processes. The accounting frameworks used to record energy consumption and TGH emission calculations are just as numerous. Globally, the sector of transport logistics is heterogeneous; its companies differ in

– Sizes: land use, number of employees, sales volume, tonnage per year, fleet size

– Business segment: number and type of core processes, logistics service provided, ownership structure

– Sustainability: awareness of sustainable operations, measures used for higher sustainability

The average values of energy demand, carbon footprint, and reduction potential vary widely. This is not only due to different efficiencies at the process level, but also to different reference frames and activities included. In addition, the appropriate mitigation measures to reduce GHG emissions must be adapted to the specific situation of the logistics service. When comparing logistics sites based on literature data, it is often not possible to find conclusive data with reference values that cover the same scope. Energy demand, for example, is scalable with the amount of floor space occupied, but is also highly dependent on the processes that take place there and their energy intensity. Therefore, the unit “m^2”, which alone does not consider the processes (e. g. transport or both transport and freezing), is not a suitable reference value without additional information. Freis et al. [86] show that if “m^3*a” is consequently chosen as a reference value for the GHG emissions of warehouses, the fully automated and generally highly energy efficient logistics center seems to perform worse than a manual warehouse with less automated processes, but also with less logistics performance. As some authors propose, a reference to the tonnage that undergoes the same cluster of logistics activities might be a good solution [84, 81]. A previous, site-wise grouping of all logistics services that are applied to the goods into clusters of similar purposes (e. g. storage, palletize and wrapping, cooling, repacking and printing) is necessary. The problem of properly describing the energy consumption of warehouses was firstly addressed by Dhooma and Baker [106], and the proposed framework was generally adopted by [23, 81, 19, 2, 7].

The difficulties of finding suitable reference values for transport-related emissions are obvious; there are measures that reduce both the energy intensity and activity factors of transports. If the remaining GHG emissions are expressed as goods-related, for example, “kg CO_2e/t” or “kg CO_2e/item”, the efforts of lowering the energy intensity factor cannot be evaluated independently. If GHG emissions are assigned to the transport performance as “kg CO_2e/tkm”, a reduction of distances traveled is neglected. Furthermore, because of the changes in the freight structure, a weight-based reference loses significance in some countries. Within the last decade, it is more often the case that volume is the limiting factor when serving markets in which the product structure shifts from bulk goods to high-value unit goods. It is also mentioned by Schrampf and Hartmann [7], who choose pallets as a reference value. Although this reference is in accordance with the Global Logistic Emissions Council framework [107], there are variations in average pallet weights from 200 to 700 kg. Nevertheless, literature shows that there are existing reference values to choose from, and carefully considering the logistics tasks to be quantified is essential for the right choice. Before mitigation measures can be applied, the actual GHG accounting must take place. This is still an issue, even though a lot of frameworks have been proposed within the last two decades [108, 71, 2, 109].

4.5 Mitigation Approaches in Literature

Most of the publications included in this review mention one or more measures to reduce GHG emissions. With reference to the IPCC emissions framework, Tables 3 to 8 show that most authors propose several mitigation measures that address different sources of GHG emissions (i. e. that reduce fuel and/or activity and/or energy intensity) (Table 9). As the IPCC decomposition approach shows, there are several independent ways to reduce GHG emissions from transport. Therefore, a joint consideration of mitigation results as a total range of a mitigation results is only permissible if the literature sources have examined the same IPCC GHG decomposition factors (a, e or f) and the same reference values or reference frameworks. As this is not the case, the values reported in the respective papers are presented in Tables 3 to 8 without a common scale. Table 10 provides a summary of the GHG mitigation measures in categories, grouped by reference frames A – F. The IPCC decomposition factors that are primarily addressed by the respective GHG mitigation measure are also counted. Although no clear assignment could be made, Table 10 shows that efficiency measures (letter "e") are widely discussed across all perspectives.

By far the greatest potential is seen in diesel substitution (40 to 70 %), regardless of the perspective taken by the publication. Fifteen of the grouped publications mention this measure. Most of the studies within this review that discuss sufficiency approaches, which aim at drastically reducing logistics activity, are not considered. Driving distances can be reduced through network optimization, and thus activity intensity, but these effects are on a smaller order of magnitude (2 to 16 %). This may be due to the fact that route planning, supported by traffic management systems, has almost reached the distance optimum in the last two decades. In addition, in the last three decades, the established consolidation centers have already reduced the distances for freight transportation [52]. While the replacement of the driving technology and the choice of transport mode belong to the strategic level, the optimization of a delivery route addresses the reduction potential at the operational level. The mitigation measures that are considered or proposed address the responsibility of the balancing framework, for example,

- City governments, legislators, port operators for context frame "A"
- Executive management of companies for context frames "B" and "C"
- Production companies, end customers or sellers for context frame "D"
- Vehicle manufacturers or drivers for context frame "E"
- On-site process management or process operators for context frame "F"

The knowledge about the actual magnitude of GHG emissions seems to be fragmented as well and is not likely to be shared across the respective areas of responsibility that are involved in logistics.

5 CONCLUSIONS

Scientific publications reviewed in this paper focus on either transport or on-site energy demands, GHG emissions or mitigation potentials. A final number of 77 publications was identified that give numerical data on either energy consumption or greenhouse gas emissions and mitigation measures. Although the number of publications is quite high, due to very different business models, background systems, sustainability awareness, particular assumptions and contextual views, comparing different studies is very difficult and – across the complete portfolio – not possible. The context view of the studies obviously influences both the methodical design and the system boundaries applied. Based on the actual status of the quantitative data and GHG mitigation measures published, it is, therefore, neither possible to identify transferable key figures nor to deviate a roadmap towards zero emissions in the logistics sector. Although the literature review gives a good overview on possible mitigation measures under discussion, the framework of action in which

Table 9: Measures to reduce the GHG outputs of road transport logistics services and processes found in literature, adapted to IPCC framework [12]

mode tkm_{mode}/tkm_{total}	fuel intensity f CO_2e/MJ	energy intensity e MJ/tkm	activity a tkm_{total}
transport via	**carbon content**	**efficiency**	**sufficiency**
Rail Waterways	Biomethane Electricity Hydrogen	Enlarged capacity Lightweight construction Payload near maximum Traffic smoothing Improved vehicle technology	Deliver less frequently Consolidation centers Local sourcing Sharing Crowdshipping Routing optimization

Table 10: Categories of GHG mitigation measures, grouped by reference frames

Logistics Context	Transport-related data on energy consumption and emissions				Vehicle-related	Site-related
Frames	A	B	C	D	E	F
IPCC factor a activity	6	5	5	6	0	4
e energy intensity	12	6	4	3	6	7
f fuel intensity (carbon)	6	2	4	2	2	0
f Replacement of Diesel	5	1	4	-	4	1
e Reducing driving distances (routing, consolidation centers)	7	5	5	4	-	-
e, f Modal shift (rail transportation)	2	1	-	-	-	-
e Better traffic flow, optimal speed	7	1	2	-	2	1
e Autonomous drive/ eco training	1	3	2	-	2	
e Higher load factor	1	1	-	2	-	-
f Carbon intensity of energy	2	-	1	-	-	1
e On-site energy efficiency	-	-	-	-	-	7
e Vehicle optimization (tires, aerodynamics, driving train, curb weight)	-	-	-	-	3	-
a, e Buildings services – energy reduction	-	-	-	-	-	4

mitigation measures can be implemented does not allow for a transfer without further adoptions.

According to the literature, the most promising design to reduce GHG emissions from logistics is to operate with higher efficiency at all levels of control-strategic, operational, tactical-combined with energy supply from renewable sources. The decision to implement a particular efficiency measure may be clearly outside the scope of a logistics company, for example almost all measures related to traffic flows. Targeting decisions to the right stakeholders is essential to fully exploit all mitigation potentials while avoiding major trade-offs.

Despite the overall good data quality, the demand for tools and standards to assess the emissions of the logistics industry is still growing in order to develop transformation pathways towards decarbonization of the transport sector [108, 3, 7]. The requirements for such tools are high due to the very heterogeneous structure of the industry: they must allow for practicable data collection and comparability within the industry, but work in a sufficiently detailed way to map business models and optimization potentials of specific locations. How such standards can look like has been intensively discussed in the literature [85, 110, 111, 3].

The complex case of the inhomogeneous logistics sector will most likely require a complex and intensive exchange of information, without losing sight of the interrelationships. The exchange of key figures, which is a very condensed form of information, is not suitable to deal with this complexity. There is a need for high granularity in both the accounting and mitigation of GHG emissions. A deeper analysis, such as an LCA, which includes both site emissions and transport-related emissions, including scope 1, scope 2 emissions of electricity production and scope 3 emissions of equipment production, can provide suitable emissions metrics for the logistics performance associated with the entire site. Mitigation measures derived from this are better adapted to a logistics company's area of responsibility. These LCAs are not mentioned in the current literature. We see this as a research gap. In the future, an integrative view of logistics emissions that uniformly considers emissions from upstream chains could provide a valuable foundation for the roadmap to net-zero GHG emissions.

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