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Heavy-Duty Vehicles charging infrastructure energy demand and factors affecting their placement in Finland

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Abstract

A notable share of greenhouse gas (GHG) emissions from road freight in Europe stems from heavy-duty vehicles (HDVs). Despite being a small fraction of the overall vehicle fleet in Finland, the contribution of HDVs towards GHG emissions is disproportionately large. European Union (EU) aims to reduce the new HDV fleets emissions to 30 % by 2030, with Finland targeting a 50 % reduction in transport sector emissions by 2030 and complete elimination by 2045. This study aims for the estimation of energy and power demand for electrification of HDVs in Finland, however the approach can be applied to other regions and countries as well. Utilizing traffic volume data from 376 traffic measurement system (TMS) points on Finland's 28 main roads, the study classifies HDVs and calculates their fuel and electrical energy consumption (EEC). The results indicate a need for 4.89 TWh of annual peak energy for 100 % electrification of HDVs, reflecting a minimum 0.614 GW power demand and requiring 1,755 chargers (each with a capacity of 350 kW at 22 h/day utilization). The analysis includes spatial mapping of energy density, energy demand, power requirements, and charging stations placement based on alternative fuels infrastructure regulations (AFIR) by EU. The obtained results can be future utilized to study local grid strength and possibility to participate in the frequency markets.

Keywords: battery electric truck; charging infrastructure; European Union regulations; energy demand; geo-spatial mapping; heavy-duty vehicles

I. INTRODUCTION

A significant portion (around 6 %) of total greenhouse gas (GHG) emissions in European Union (EU) comes from heavy-duty vehicles (HDVs), including buses and coaches (European Commission Climate Action, 2023). These vehicles also contribute 25 % of the EU's total CO_2 emissions in the road freight transport sector (European Commission Climate Action, 2023)(European Environment Agency, 2022).

This highlights the critical role of HDVs in climate change mitigation and points towards the sector's essential transformation, given the EU's stringent regulations to limit these emissions. A recent regulation EC 2019/1242 by EU parliament which addresses the HDVs emission, points the manufacturers in the same direction by requiring 15 % reduced emissions by 2025 and a 30 % reduction by 2030 (European Union, 2019). The most recent revision in the regulation EU 2024/1610 sets more ambitious emission reduction goals for new HDV fleets: by 2030 it should be reduced to 45 %, by 2035 it should be 65 % and it should be up

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to 90 % in 2040 (Council of European Union, 2024).

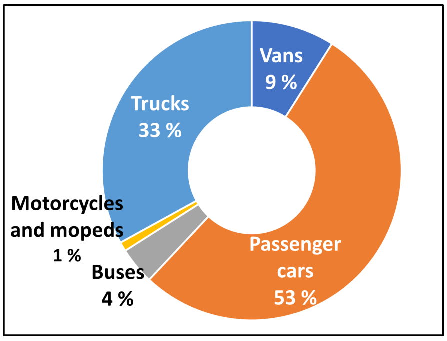


Figure 1: Finland's GHG emissions for all road transport categories in 2021 (Siljander et al., 2023).

Achieving these targets is vital for Finland where road transport contributed to almost 95 % of domestic transportation GHG emissions in the year 2021 (Siljander et al., 2023). Within these road transport emissions, HDVs contributed 33 % of the total as depicted in Figure 1. Overall, transport sector (excluding air transport) in Finland was responsible for over 20 % of its total GHG emissions in 2021 (Siljander et al., 2023). In comparison with the reference year of 2005 emissions (11.8 million t CO_2-equivalent) from transport sector (Statistics Finland, 2023b), Finnish government's target is to halve those emissions by 2030 and eliminate them by 2045 (Service Sector Employers Palta and Finnish Freight Forwarding and Logistic Association and Finnish Information Centre of Automobile Sector and Association of Logistic Enterprises in Finland and Finnish Public Transport Association and Finnish Bus Association and Intelligent Transportation Society of Finland, 2021). However, significant efforts would be needed to achieve the stricter Finnish target of carbon neutrality for all sectors combined, by 2035 under the new act on climate change (Ministry of Environment, Finland, 2022). Under this act the emission reduction targets are 60 %, 80 %, and 90–95 % to be achieved by 2030, 2040, and 2050, respectively, as depicted in Figure 2.

Various sources of renewable and zero-emission fuels are currently being considered in order to realize future emission targets. These include bio-fuels such as fatty acid methyl ester diesel, hydrotreated vegetable oil diesel, bio-gas, and bio-gasoline. Additionally, e-fuels like hydrogen-based fuels such as methanol and synthetic gases present promising alternatives to traditional fossil fuels (IEA Bioenergy, 2021). However, the optimal use of these resources is debatable. The question arises whether valuable biomass should be utilized for fuel production or if it is more advantageous to focus on fossil-free hydrogen-based e-fuels. Nevertheless,

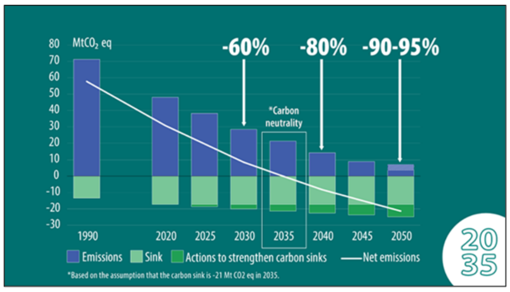


Figure 2: Emission reduction targets under The New Climate Change Act in Finland. (Finnish Government, 2022).

due to large biomass potential of Finland, bio-fuels represented 15.7 % of overall energy consumption in road transport sector in 2022. Bio-diesel, bio-gasoline and bio-gas were three of the most notable bio-fuels with 17.8 %, 9.8 % and 97.9 % of energy share in diesel, gasoline and compressed/liquified natural gas consumption categories respectively (Statistics Finland, 2023a). The shares of bio-gasoline and bio-gas have shown a growth of 0.9 % and 41.8 % from the last year, as opposed to bio-diesel that has a decline of 4.4 % in its share. On the contrary, e-fuels production is in research phase with few investment proposals published in 2022, for a total of 1 GW green hydrogen and 0.5 GW of e-methane production (IEA, 2022). However, cost of these technologies is significantly higher than direct electrification of HDVs because of the low efficiency of power-to-gas/liquid systems.

Additionally, the electrification of transport presents a viable alternative that merits consideration, due to absence of exhaust CO_2 emissions. According to Statistics Finland, electricity has 1 % share of total energy consumption in road transport sector in 2022 (Statistics Finland, 2023a), which is almost 100 % growth from the previous share of 0.5 % in 2021 (IEA, 2022). Furthermore, 2023 has seen a year-on-year growth of 66.5 % in the use of electrical energy in road transport (Statistics Finland). The rapid growth of electricity share indicates the incline towards the electrification of transport sector, driven by the Finnish government's progressive subsidies of 1.5 to 8.5 million €/year for the charging infrastructure development between 2019 and 2025 (Ministry of Transport and Communications, Finland, 2021). The sharpest impact in emissions reduction by electrification of vehicle fleet and corresponding infrastructure can occur from HDVs, since these vehicles represent a disproportionately high share (around 33 %) in total road transport emissions as compared to their smaller share of 1.83 % in the active vehicles stock in 2021 (Statistics Finland, 2024). Furthermore, Eurostat data for road freight transport performance by distance class in

2022 indicates that for Finland, the performance (million tonne – kilometre) has decreased by 15.4 % with respect to 2021 for distance class of <150 km, indicating a decrease in regional road freight transport. At the same time, it has increased with a growth rate of 7 %, 12.7 % and 9.8 % for distance classes of 150–299 km, 300–999 km and ≥1000 km respectively. This underscores an overall increase in performance and significant emissions reduction potential that the long haul road freight transport electrification can bring, with highest potential in 300–299 km distance class (Eurostat, 2024).
Despite the great potential, challenges remain. For instance, due to their sheer size and front cross sectional area, HDVs in general necessitate more energy to overcome aerodynamic drag, rolling resistance, and gravity, though advancements in aerodynamics, tires, and wheel design have mitigated losses in newer models. Various aerodynamic and tire rolling resistance technologies have been shown to reduce fuel consumption (FC) for long-haul and regional-haul trucks by 11.9 % and 8.4 %, respectively (Sharp et al., 2013; Buscariolo et al., 2020).

The FC of HDVs is influenced by vehicle weight, design, fleet composition (defined by (Liimatainen and Pöllänen, 2010) as euro factor), operational efficiency, driving conditions, and regulatory policies (Liimatainen et al., 2019). Shifts to newer Euro standards generally enhance fuel efficiency due to better design, with Euro 1 vehicles shown to consume 6.9 % less fuel compared to Euro 0 vehicles. Reductions are 7.6 %, 5.2 %, 10.1 %, and 9.1 % for Euro 2, 3, 4, and 5 respectively (Liimatainen and Pöllänen, 2010). Operational efficiency, including load optimization and minimizing empty runs, also significantly reduces energy usage. Urban driving conditions and frequent stopping negatively impact FC (Liimatainen et al., 2019). Kolařík (Kolařík et al., 2013) found that longer hauling distances lower FC due to fewer loading/unloading and less frequent travel on forest roads, with Euro 5 class tractor trailer (TT) consuming less fuel than Euro 3 class TT. Furthermore, regulatory policies concerning Euro standards, allowable weight limits and energy efficiency agreements are essential indirect measures for achieving energy savings in HDVs. For example, Palander's (Palander, 2017) study on increased gross vehicle weight (GVW) limits in Finland demonstrated that optimizing GVW could enhance FC efficiency, with a long-term reduction in FC per tonne – km estimated at 15.5 %.

However, concerning battery capacity and payload in long-haul road freight transport, data collected from multiple HDVs manufacturers reveals the modern progressive solutions provide a maximum battery capacity of around 1000 kWh with a range of up to 885 km and a payload capacity of almost 32 t corresponding to gross combination weight (GCW) of 44 t (Hall and Lutsey, 2019). This looks promising in terms of range covering the most of distance class 300–299 km, but is insufficient when it comes to the allowable GCW limit of 76 t for HDVs in Finland implemented in 2013 under an amendment to Finnish legislation (Ministry of Transport and Communications, Finland, 2013).

The battery capacity versus payload dilemma is significant, with advancements in battery chemistry and capacity (measured in kWh/kg and km) being important. Lithium-air batteries have been proposed as a promising solution with projected specific energy in the range of 0.5–0.9 kWh/kg and 550 km driving distance potential, that is five times higher than the current lithium-ion batteries (Liang et al., 2022). This advancement in Lithium-air battery technology could potentially lead to a five-fold reduction in battery weight for the same energy capacity.

Additionally, compliance to working hour regulation EC 561/2006 also poses a challenge on the way to electrification of HDVs (European Union, 2006). As per the regulation, after each driving period of 4.5 hours, drivers must take a continuous break of at least 45 minutes, except when they are going to start their daily or weekly rest period (European Union, 2006). Currently, 350 kW chargers can charge regional-haul trucks with a GVW of up to 18 tonnes and a range of 350 km in under 45 minutes. However, for trucks with greater GVW, charging times exceed this limit. This highlights the need for megawatt-sized chargers and advancements in HDVs charging capabilities, as most electric HDVs on the market can only receive up to 400 kW, resulting in charging times of 1–2 hours for 0–80 % battery capacity. The megawatt-class charging is now entering practical market use. European companies, like Kempower and ABB have introduced their 1.2 MegaWatt chargers (Kempower, 2025; E-mobility, 2025) and new Megawatt Charging System standard reaches up to up to 3.75 megawatts (CharIN, 2025). Tesla's new V4 “Megacharger” infrastructure is reported to deliver up to 1.2 MW for the latest Semi Truck models as well (Phoon, 2024; Electrive, 2025). The megawatt charger configuration could reduce an 80 % recharge of an 800 kWh battery (a reasonable long-haul pack estimate) from 1–2 hours (at 400 kW) to just 32 min at 1.2 MW. Additionally, scheduling logistics—such as fitting charging times around operational schedules of harbors, logistics hubs and food stores etc.—pose further complications.

Furthermore, initial capital expenditure in connection with conversion from fossil fuels to battery-electric HDVs can also be a significant hurdle. A research group in the United States of America estimated that in 2020, a battery-electric TT (≥16.5 tonnes GVW) for long-haul operations costs $49,000 more than a comparable diesel model. Diesel trucks are projected to remain cheaper until around 2026, after which battery-electric models will become more cost-effective. For delivery trucks (9.75–13 tonnes GVW) used in the regional-haul sector, the initial cost of a battery-electric vehicle was $12,000 higher in 2020, but by 2030, it is expected to be $30,000 lower (Hall and Lutsey, 2019).

Moreover, the development of charging infrastructure must also balance public and private (transport companies) needs in terms of upfront costs, fleet schedules, and EU regulatory requirements. International Council on Clean Transportation (ICCT) estimates that for long-haul TT, charging infrastructure cost can represent a share between 10 % ($110,000/vehicle) to 7 % ($70,000/vehicle) of total cost of ownership (TCO), decreasing over the years from 2025 to 2030. For regional-haul HDVs, the same cost ranges from 13 % ($40,000/vehicle) to 9 % ($27,000/vehicle) of TCO, due to economy of scale. It is therefore imperative at initial stage of development to take into account the schedules of public and private HDV fleets, in order to optimize the utility of charging infrastructure (Hall and Lutsey, 2019). It is equally important to consider alternative fuels infrastructure regulation (AFIR) regulations (Council of European Union, 2023) regarding minimum power and distance requirements for core and comprehensive network roads in Finland, while planning for the infrastructure development.

The potential of electrification in HDVs freight transport necessitates significant investment in battery-electric trucks, charging infrastructure, and renewable energy. However, sufficient volume of battery-electric HDVs is needed to justify this investment, which in turn depends on having the infrastructure in place. Government support is essential to bridge this gap until the system becomes self-sustainable through economies of scale. This study aims to find a possible solution to this problem by using available technological advancements and one or more case study calculations and gauge country level electrical energy demand (EED) of HDVs for 100 % penetration, thereby aiding policymakers and planners in arranging the necessary investments.

Finland's unique geographical and logistical landscape demands careful planning for the electrification of HDVs. The country is sparsely populated with 5.6 million inhabitants (Statistics Finland). There are a total of 77,804 km of Highways in Finland (Statistics Finland). While the 28 main roads, marked with "valtatie (VT)" from VT1 to VT29 (VT17 excluded), comprise of 8,957 km in total. Logistic hubs are primarily located in the south of the country near capital area. Despite having a strong electricity network with a production of 69,142 GWh in 2022, the volatility of electricity prices is usually quite high due to capacity constraints stemming from a net import of 12,517 GWh energy (Statistics Finland). On the contrary, in the road transport sector, only 1.6 % of total energy consumption came from electrical sources in 2023, highlighting the need for accelerated electrification of the sector (Statistics Finland). Therefore, it makes sense to assess the additional electrical energy demand, corresponding size and location of charging stations and network strengthening requirements.

Although, geo-spatial approach has been extensively used to assess charging infrastructure penetration rates for light electric passenger vehicles (Melliger et al., 2018; Bräunl et al., 2020; Guo et al., 2018; Hilton et al., 2018; Wang et al., 2020). Few studies discuss the comprehensive electrical energy demands of charging infrastructure for HDVs (Danese et al., 2021; Samet et al., 2021; Shoman et al., 2023; Teoh et al., 2018). Most focus only on specific areas or key roads. For instance, (Danese et al., 2021) studied Norway's highway E18, analyzing power demand for static, induction, and hybrid charging scenarios based on electrical grid proximity. Similarly, (Samet et al., 2021) approached a country scale by selecting a few key highways/motorways for geo-spatial mapping. Using the battery electric vehicle potential model and road freight transport surveys, they calculated charging infrastructure energy demands for trucks over 3.5 t GVW in Finland and Switzerland. Their results showed that for a 91 % electrification scenario with 98 % depot charging and 2 % on-road charging, Finland's 2,384 km of roads would require 3,457 GWh annually. However, the outdated travel data and lack of vehicle type segregation make the results less reliable today. It is important to consider that the composition of traffic volume of different HDVs directly affects energy demand. Additionally, the existing mapping does not incorporate EU's AFIR regulations demanding dedicated HDV charging pools and other requirements.

In another recent EU-wide study, (Shoman et al., 2023) assessed charging infrastructure needs for a 15 % battery electric truck (BET) penetration scenario using ETISplus data. This data, up-scaled for truck traffic and freight volume up to 2019 at the Nomenclature of Territorial Units for Statistics-3 (NUTS-3) level, also included a source from Statistics Finland based on 10,000 sample surveys (Finland, 2022). The study estimated an energy demand of 518 MWh/day for 15 % BET penetration by 2030, with 142 charging areas in Finland spaced 25–35 km apart—denser than

EU’s AFIR guidelines. However, it did not address the power demand in the analysis.

The use of survey-based data in their study presents challenges due to sampling (4–5 %) and non-sampling errors, with only 25–30 % actual responses from the 10,000 samples, leading to less precise results as the data is broken down in more detail Finland (2022). Additionally, the evaluated freight volume was then used to indirectly calculate traffic volume followed by energy demand, raising doubts about the accuracy of projections. In contrast, this study uses real traffic volume data, offering a more precise estimate of energy demand. While (Shoman et al., 2023) estimated 518 MWh/day for long-haul trucks (>12 t) in 2030, our findings show a significantly higher demand—around 2.01 GWh/day for 15 % BET penetration in 2023, which includes all heavy-duty vehicles (HDVs >3.5 t).

Moreover, adjusting the distance between charging stations (as shown by (Funke and Plötz, 2017) for Germany) to meet AFIR rules would reduce the number of locations needed, simplifying infrastructure planning. The inclusion of power demand evaluation in our study provides additional critical insights for grid management and infrastructure development, offering a more comprehensive and actionable framework for advancing Finland’s electrification goals.

Long-term statistical data availability in Finland helps with the accurate assessment of energy demand, capacity calculation and infrastructure planning. However, the main prerequisites are the FC for different size of HDVs and brake thermal efficiency. Several studies have adopted integrated methods to determine average FC for different types of HDVs on rural roads or motorways (Weller, 2020; Söderena et al., 2021; Liimatainen and Pöllänen, 2010). For average vehicle electric energy consumption (AVEEC) estimation, brake thermal efficiency value for diesel engines is required. Various studies have investigated brake thermal efficiency in HDVs and reported up to 46 % for diesel engines as discussed in more detail under section II-II.1 (Söderena et al., 2021; Ragon and Rodríguez, 2021).

This study calculates the additional energy, power, and charger demand by utilizing evaluated FC and AVEEC data, along with traffic volumes on main roads. The methodology used is similar to that of (Liimatainen et al., 2019), with the subsequent placement of charging infrastructure following AFIR requirements (Council of European Union, 2023).While the primary aim is to assist policymakers and decision-makers in organizing and managing investments for charging infrastructure development in Finland, the methodology used is adaptable to other regions or countries, taking into account local regulations for charging station placement and traffic volumes. It aids in determining local power and energy demand, providing information for future analysis regarding local grid strength, possibility to participate in frequency support markets. In addition, this study allows to evaluate the potential total capacity from HDV charging stations that can be provided for Fast Frequency Reserve services (Tupitsina et al., 2024).

The study carried out in this research includes the following:

- Measurement of traffic volume at 376 traffic measurement system (TMS) points on all main roads in Finland for 2023.
- Classification of HDVs as defined by Fintraffic (a special assignment group operating under the Ministry of Transport and Communications Finland, responsible for safety and smoothness of all types of traffic): type 2 (trucks without trailers), type 4 (trucks with semi-trailers), type 5 (trucks with full trailers), and type 9 (high capacity trucks).
- Comparison of two different approaches to calculate FC and AVEEC for HDV types.
- Selection of charging stations sizes and locations based on AFIR guidelines dedicated to HDV infrastructure.
- Spatial mapping of energy demand, energy density, charging stations, and power requirements for all 28 main roads in Finland.

When considering the targets of this research, the study will exclude the following, to avoid complexity:

- Minimum power requirements for each charging station as per AFIR regulations, to avoid complexity.
- Cost estimation for HDVs charging infrastructure.
- Techno-economic evaluation of battery-swapping stations as an alternative to HDV charging stations.

Moreover, the research carried out in this study is limited due to the lack of detailed information, resulting in the exclusion of the following factors:

- Waiting times at charging stations and driver break time regulations.
- The energy requirements for charging at operator terminals or off-loading terminals are not estimated.
- Optimization of charging station locations based on proximity to the existing electrical grid network, and dedicated safe HDVs parking spaces.

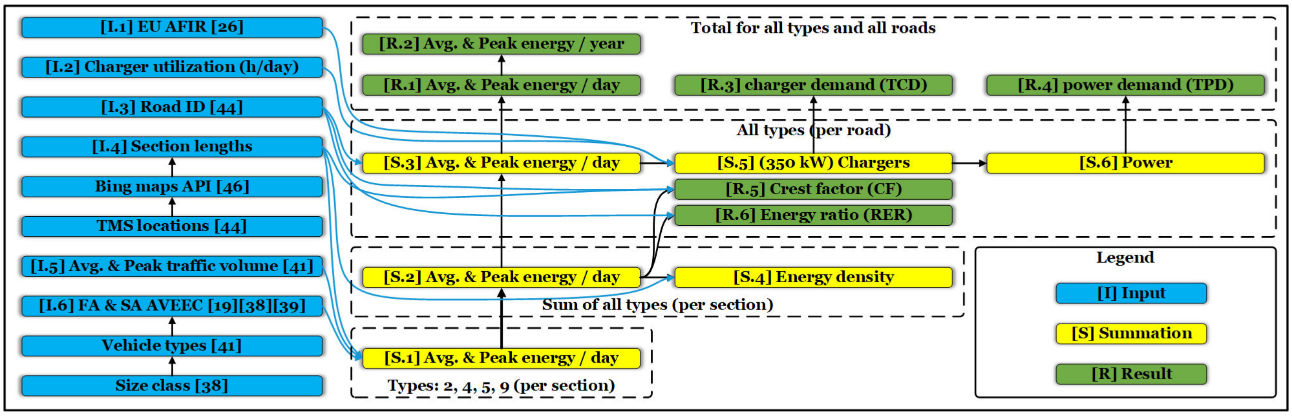


Figure 3: Demands assessment model used in this study.

II. DEVELOPMENT OF DEMAND MODEL

This study employs quantitative data and a demand assessment model to evaluate the impact of current HDV traffic volume across all 28 highways in Finland on future energy requirements of charging infrastructure for a 100 % transition to battery electric vehicles. The model is organized into color-coded cells: inputs (blue), summations (yellow), and results (green), as illustrated in Figure 3. Each cell is labeled as "X.n," where "X" represents the type of cell, and "n" is the cell number. These labels will be referenced throughout the document. This section explains the inputs and assumptions used in the model and details the calculation process for demand assessment, with results presented in the following section.

II.1. Input data for the model

The input data points as shown in Figure 3 serve as critical inputs for the demand assessment model, offering a comprehensive view of traffic composition, vehicle specifications, and road characteristics essential for accurately estimating future energy demands and charging infrastructure needs for a 100 % transition to battery electric HDVs. Detailed vehicle information aids in calculating the EED, while traffic volumes, road lengths, and AFIR rules help determine the placement and recurrence of charging stations. Accurate estimation of the proposed charging infrastructure's capacity also requires assumptions about charger power and operational time. Each of these input data points will now be discussed in detail in the following list.

II.1.1. EU alternative fuels infrastructure regulation for charging station location selection (I.1)

HDVs charging infrastructure regulation by the EU for the Trans-European Transport (TEN-T) network (Council of European Union, 2023) as summarised later in Table 1 was used to select suitable combined charging station locations, ensuring a uniform approach across the entire network based on daily average traffic volume in 2023 and designated limit of 60 km or 100 km between charging stations. HDV charging station locations were selected out of the TMS points locations database. The combined length of the VT1 to VT29 roads network is 8,957 km, as calculated using Bing Maps (Microsoft, 2024). Of this, approximately 67 % (6,002 km) are part of the TEN-T project by the EU. To simplify the calculations and maintain uniformity, this study applies the following assumptions for 100 % of the network:

- Daily average traffic volume: Use the daily average traffic volume in 2023 to determine the designation of 60 km or 100 km between charging stations (Council of European Union, 2023).
- Designation criteria: Sections with less than 800 average traffic volume or those falling under the comprehensive network are designated as 100 km sections. Otherwise, 60 km designation is applied for the core network.
- Distance tolerance: It is considered acceptable for successive charging stations to be spaced between 50 and 105 % of the designated kilometers.
- Selection criteria: If two successive suitable points exceed the designated distance, both points are selected for charging stations. Points are also selected if the preceding point to the exceeded point is within less than 50 % of the designated distance.

Table 1: EU’s AFIR 2023/1804 guidelines for HDV charging infrastructure.

AADTV	**Road network**	**Service**	**Designated limit** [km]	**Min. power** [kW]	**Total min. power** [kW]	**Individual O/P** [kW]
≤ 2000	Core	BD - CL - 100 % PE	60 (100*)	2800	5600—7200	2 × 350
		ED - SL - 50 % PE			2800—3600	
	Comprehensive	BD - CL - 100 % PE	100	1400	2800—3000	1 × 350
		ED - SL - 50 % PE			1400—1500	
>2000	Core	BD - SL - 100 % PE	60	2800	5600—7200	2 × 350
	Comprehensive	ED - SL - 100 % PE	100	1400	2800—3000	1 × 350

Abbreviations: BD: Both direction; ED: Each direction; CL: Combined location; SL: Separate location; PE: Power for each; ATV: Annual average daily traffic volume. *: If AADTV <800

- Road intersections: At intersections of core and comprehensive networks, if the preceding network’s last point is at half or less than half of the designated distance, that section length is considered for the next region’s first point calculation.

- End locations: Regardless of distance rules, ending locations of each road are always selected for charging stations.
  Note that the starting and ending locations for most roads lack TMS points, resulting in no traffic volume data at these locations. To address this, traffic volume data was divided based on the direction of travel on the road, assuming that oncoming traffic from the last TMS point before the end also passes through the ending location. For simplification, this study assumes combined charging stations for both directions of travel at selected locations.

The selection criteria for charging station locations primarily follows EU regulations (table 1), with a few assumptions made due to the existing placement of TMS points. EU regulations consider two successive charging stations 120 km (120 %) apart as compliant, but do not specify a lower limit. This study assumes a lower limit of 50 % and an upper limit of 105 % for selecting charging station locations for both types of road networks. Additionally, a minimum power requirement of 350 kW is used for each charging station to reflect actual energy demand in 2023, instead of the 2800 kW and 1400 kW specified in EU regulation for charging stations in core and comprehensive networks, respectively. Furthermore, a rule for road network intersections is assumed to maintain consistency in all relevant cases.

II.1.2. Individual charger assumptions

EU regulations (Council of European Union, 2023) require a minimum individual charger power output to be at least 350 kW, the same was selected for our analysis in this study. Additionally, a maximum charger utilization rate of 22 hours per day was selected to account for maximum observed peak power duration in 2023 winter for Finland (Fingrid, 2024) and was used to evaluate all related demand matrices. However, a sensitivity analysis for different utilization rates (I.2) was done as later explained under section III-III.2.

II.1.3. Road characteristics

To enable the assessment of energy consumption by certain number of vehicles for a section of road between adjacent TMS points and geo-spatial mapping of charging stations, it is important to define the road characteristics. Initially, road IDs (I.3) for 28 main roads and location data from 376 TMS points were gathered from Fintraffic (Fintraffic, 2024). Subsequently, total road lengths, section lengths (I.4) (SL_i) between TMS points, and distances from the last TMS points to the road endpoints (Bing Maps, 2024) were calculated. This evaluation was performed using Fintraffic coordinates (Fintraffic, 2024) and the Bing Maps API (Microsoft, 2024) under a free-use license.

II.1.4. Traffic Volume (I.5)

The primary data source for this research is the TMS reports from Fintraffic (Fintraffic, 2023). The TMS utilizes over 450 road traffic measurement devices across Finland, capturing data such as traffic volume, direction of travel, lane allocation, speed, and vehicle category. Although data has been available since 2010, this study focuses specifically on 2023 traffic volume data from 376 TMS points, recorded at a daily resolu-

Table 2: Finland's road freight transport by payload capacity in 2022 (Eurostat, 2023).

Class	Payload	million t-kms driven
1	9.5 t or less	333
2	From 9.6 to 15.5 t	763
3	From 15.6 to 20.5 t	1,303
4	From 20.6 to 25.5 t	1,001
5	From 25.6 to 30.5 t	1,605
6	Over 30.5 t	25,586
Total		30,590

tion for vehicle types 2, 4, 5, and 9. Peak and average traffic volumes (TV) for 2023 were extracted out of this empirical data for all TMS points to serve as key inputs for the demand assessment model.

II.1.5. Vehicle's average electrical energy consumption (I.6)

Fintraffic data did not clarify the GVW for each type of HDV. Therefore, to determine the average vehicle electrical energy consumption (AVEEC) for each HDV type (j), multiple sources for GVW were employed. The size classes, as presented in Table 3, were then used to calculate AVEEC, which serves as an important input for evaluating the energy demand of the charging infrastructure.

Initially, size sub-classes and the corresponding average FC were incorporated from doctoral dissertation carried out at Graz University of Technology (Weller, 2020). This dissertation is part of handbook for emission factors for road transport 4.1, updated in September 2019, which provides a comprehensive database of emission factors and FC data for each vehicle category across relevant traffic scenarios, widely used in various studies. The sub-classes for rigid truck (RT) included >3.5–7.5 t, >7.5–12 t, >12–14 t, >14–20 t, >20–26 t, >26–28 t, >28–32 t and >32 t. Whereas. the sub-classes for TT/articulated truck (AT) included >3.5–7.5 t, >7.5–14 t, >14–20 t, >20–28 t, >28–34 t, >34–40 t, >40–50 t, >50–60 t and >60 t.

For GVW up to 68 t, FC (L/100km) data derived from chassis dynamometer measurements and real-world testing (Weller, 2020) for both RT and TT/AT and for motorways was used that included at least one test vehicle from each sub-class. Missing GVW and payload capacity data for certain sub-classes were assumed based on typical kerb weight values. For TT/AT vehicles and >68–78 tonnes GVW, FC data was taken from (Söderena et al., 2021), derived from actual trips on the Helsinki to Oulu road (~600 km). Missing tare weight information in this case was estimated using typical HDV models in the market.

Next, payloads for all sub-classes for both RT and TT/AT were calculated by utilizing available kerb or tare weights. AVEEC values were then calculated using known average FC (Weller, 2020)(Söderena et al., 2021) for two different approaches, "First Approach (FA)" and "Second Approach (SA)" against each payload. Using different approaches (shown later in Figure 4) helped in validating the FA AVEEC results that originate from real-world measurements done on diesel based HDVs, with the SA results that replicate AVEEC trend from a prior study (Liimatainen and Pöllänen, 2010).

In FA AVEEC (kWh/km) was calculated by using known average FC_{FA} and brake thermal efficiency (η_{FA}) between diesel and electric system of the vehicle as shown in (2.1). A 2021 International Energy Agency study reported efficiencies up to 46 % for top diesel engines and 37 % for spark ignition methane engines (Söderena et al., 2021). A 2019–2020 ICCT study reported a maximum average efficiency of 44.5 % for diesel engines (Ragon and Rodríguez, 2021). Recognizing that not all diesel engines achieve peak efficiency, a conservative brake thermal efficiency (η_{FA}) of 44 % is used in FA. Given that diesel HDVs represent 96.5 % of the traffic stock in 2023 (Statistics Finland, 2024), this efficiency is considered representative of all HDV types in the calculation for $AVEEC_{FA}$ (kW h/km). A conversion factor of 9.92 (kW h/L) from UK government issued conversion factors list for GHG reporting in 2023 (Department for Energy Security and Net Zero, 2023) is also used in (2.1) for liter (L) to kWh conversion.

$$AVEEC_{FA} = \frac{FC_{FA} \times 9.92 \times \eta_{FA}}{100} \quad (2.1)$$

The SA used a broader perspective and first generated own average FC_{SA} (L/100km) values using (2.2) from (Liimatainen and Pöllänen, 2010) that takes GVW as input, then converts these to FC_{SA} for vehicle weights >3.5–78 tonnes. The average FC is initially computed for Euro 0 HDVs. For other emission classes (Euro 1 to Euro 5/6), the result is adjusted by multiplying with factors of 0.931, 0.924, 0.948, 0.899, and 0.909, respectively, to account for improvements in engine efficiency over time (Liimatainen and Pöllänen, 2010). The resultant average FC values correspond to rural free-flow traffic, which is relevant to this study's focus on rural roads and motorways.

$$FC_{SA} = 5.9463 \times W^{0.5515} \quad (2.2)$$

$$AVEEC_{SA} = \frac{FC_{SA} \times 9.794 \times \eta_{SA}}{100} \quad (2.3)$$

Table 3: Calculated final AVEEC values assigned to HDV types.

HDV type	**Size class**	**AVEEC$_{FA}$** [kW h/km]	**AVEEC$_{SA}$** [kW h/km]
Type 2	RT (>3.5 t – 32 t)	1.32	1.32
Type 4	TT/AT (>3.5 t – 68 t)	1.93	1.99
Type 5	TT/AT (>3.5 t – 68 t)	1.93	1.99
Type 9	TT/AT (>68 t – 78 t)	2.31	2.30

FA: First Approach; **SA:** Second Approach; **RT:** Rigid Truck; **TT/AT:** Tractor Trailer/Articulated Truck

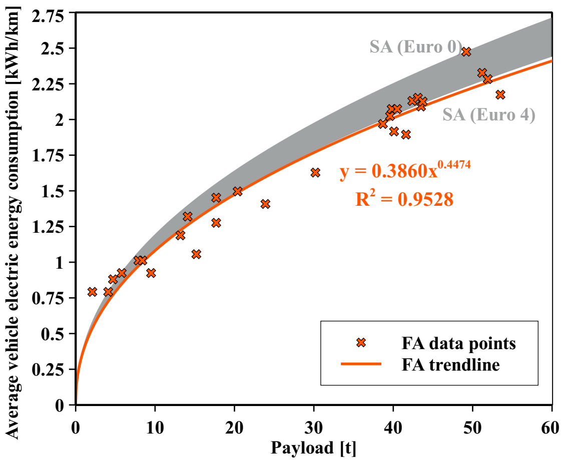


Figure 4: AVEEC for all HDVs against payload capacity, where FA is based on measured data, and SA is based on (Liimatainen and Pöllänen, 2010).

A conversion factor of 9.794 (kWh/L) for L to kWh and a factor of 2.5 (corresponding to 40 % brake thermal efficiency (η_{SA})) as the average ratio between diesel FC and electrical energy consumption (EEC) from (Liimatainen and Pöllänen, 2010) are then used in (2.3) to reproduce the (Liimatainen and Pöllänen, 2010) results in the form of AVEEC$_{SA}$ (kW h/km) as done by (Liimatainen et al., 2019). The factor of 2.5 is an average of the efficiency differences, ranging from 2.7 (37 %) to 2.4 (41.67 %) across Euro classes. Although specific efficiencies for each Euro class are unavailable, using this average factor results in multiple similar AVEEC trends (as shown later on in figure 4) rather than a single trend line.

While the first approach uses the recent factor values, the second approach retains the existing factors from (Liimatainen and Pöllänen, 2010) to replicate the results. This ensures consistency with prior analyses while accounting for variations in efficiency differences across Euro classes.

Subsequently, AVEEC values for both approaches against each payload were grouped based on the respective payload class (c) (see table 2) from (Eurostat, 2023). These group AVEEC values from payload classes (c) along with their true vehicle performance (VP) share in million tonne-kilometers driven for 2022 (Eurostat, 2023) were then used to determine AVEEC$_j$ for vehicle types (j = 2, 4, 5, and 9) (Fintraffic, 2023) using following equation (2.4):

$$\text{AVEEC}_{\text{FA or SA},\, j} = \frac{\Sigma_{c=1}^{m} \text{AVEEC}_{\text{FA or SA},\, c} \times \text{VP}_c}{\Sigma_{c=1}^{m} \text{VP}_c}, \tag{2.4}$$

where maximum value (m) of payload class (c) varies based on the type j i.e. for type 2, $m = 3$; for type 4 and 5, $m = 6$; for type 9, $m = c = 6$. The resultant average vehicle electrical energy consumption for FA (AVEEC$_{FA}$) and SA (AVEEC$_{SA}$) are shown in Table 3, where the Euro 5/6 trend was chosen for demand calculations in case of SA.

Figure 4 shows AVEEC versus payload (tonnes) for vehicles with a gross vehicle weight (GVW) from >3.5–78 tonnes. The FA trend line, defined by $y = 0.3860 \times x^{0.4474}$ with an R^2 value of 0.9528, indicates a strong fit, showing AVEEC increases with payload but at a decreasing rate as payload goes up for bigger HDVs. The FA incorporates a more recent 44 % brake thermal efficiency value compared to the SA, which uses an older 40 % efficiency value. Due to unavailability of specific efficiencies for each Euro class trend in SA, and using the average efficiency for all euro classes, results in multiple similar AVEEC trends (as shown in Figure 4) rather than a single trend line closely following the FA trend. Overall, it can be observed that measured data provides a good fit for the electrical energy consumption estimation by including efficiency maps of different engine types in HDVs corresponding to modern vehicle design used in measurements. Therefore, the measured data of FA are used in the study. Moreover, it better captures road conditions in Finland as measured data includes details about the terrain of the route.

Initial measurements from a recent study (Tuviala et al., 2024) indicate that for vehicles of 60-ton class, the trend-line provided can overestimate electrical energy consumption by approximately 5–10 % under summer conditions. However, during winter, energy consumption is expected to increase due to additional energy requirements to drive under adverse weather conditions and heating. Furthermore, batteries require heating in cold weather to maintain efficient operation, whereas diesel engines may experience a slight efficiency boost due to the availability of denser air. Therefore, the trend line provided serves as an average estimate across different scenarios.

II.2. Calculation process

In this study, the following calculations, as shown in figure 3, were performed for the analysis based on the available input data:

1. Traffic volume per day: Available peak and average traffic volumes ($\widehat{\mathrm{TV}}_{i,\,j}$ and $\overline{\mathrm{TV}}_{i,\,j}$) of each section ($i$) was aggregated by type of vehicle (j) to get the peak and average traffic volumes ($\widehat{\mathrm{TV}}_i$ and $\overline{\mathrm{TV}}_i$) for all types of vehicles (see equation (2.5)). Road-wise peak and average traffic volumes ($\widehat{\mathrm{TV}}_k$ and $\overline{\mathrm{TV}}_k$) for each road (k) were then calculated by taking the average of $\widehat{\mathrm{TV}}_i$ and $\overline{\mathrm{TV}}_i$ over total number of sections (n) in the road (see equation (2.6)). Finally, road-wise peak and average traffic volumes ($\widehat{\mathrm{TV}}_k$ and $\overline{\mathrm{TV}}_k$) for all types of vehicles were accumulated (see equation (2.7)) up to last road ($r = 28$) to get peak and average total traffic volume ($\widehat{\mathrm{TTV}}$ and $\overline{\mathrm{TTV}}$).

$$\mathrm{TV}_i = \Sigma_{j=2}^{9}\mathrm{TV}_{i,\,j} \tag{2.5}$$

$$\mathrm{TV}_k = \frac{\Sigma_{i=1}^{n}\mathrm{TV}_i}{n} \tag{2.6}$$

$$\mathrm{TTV} = \Sigma_{k=1}^{r}\mathrm{TV}_k \tag{2.7}$$

2. Electrical energy consumption per day (S.1, S.2, S.3, R.1): Peak and average sectional electrical energy consumption ($\widehat{\mathrm{SEEC}}_{i,\,j}$ and $\overline{\mathrm{SEEC}}_{i,\,j}$) for each type were evaluated utilizing $\widehat{\mathrm{TV}}_{i,\,j}$ and $\overline{\mathrm{TV}}_{i,\,j}$ respectively:

$$\mathrm{SEEC}_{i,\,j} = \mathrm{AVEEC}_j \times \mathrm{SL}_i \times \mathrm{TV}_{i,\,j}, \tag{2.8}$$

where SL_i is section length.

Peak and average sectional electrical energy consumption for all vehicle types ($\widehat{\mathrm{SEEC}}_i$ and $\overline{\mathrm{SEEC}}_i$) are evaluated as:

$$\mathrm{SEEC}_i = \Sigma_{j=2}^{9}\mathrm{SEEC}_{i,\,j} \tag{2.9}$$

Peak and average road-wise electrical energy consumption ($\widehat{\mathrm{REEC}}_k$ and $\overline{\mathrm{REEC}}_k$) over all sections ($i$) of a road ($k$):

$$\mathrm{REEC}_k = \Sigma_{i=1}^{n}\mathrm{SEEC}_i \tag{2.10}$$

The total peak and average electrical energy demand ($\widehat{\mathrm{TEED}}$ and $\overline{\mathrm{TEED}}$) up to last road (r) are given as:

$$\mathrm{TEED} = \Sigma_{k=1}^{r}\mathrm{REEC}_k \tag{2.11}$$

3. Total yearly peak and average electrical energy demand (R.2):

$$\text{Yearly TEED} = \mathrm{TEED} \times 365 \tag{2.12}$$

4. Energy density (S.4) (ED_i) (MWh/km): Assessed for each section's (i) $\widehat{\mathrm{SEEC}}_i$:

$$\mathrm{ED}_i = \frac{\widehat{\mathrm{SEEC}}_i}{\mathrm{SL}_i} \tag{2.13}$$

5. Chargers demand (S.5, R.3): For each selected location (l) of charging station, peak and average charger demands ($\widehat{\mathrm{CD}}_l$ and $\overline{\mathrm{CD}}_l$) were calculated:

$$\mathrm{CD}_l = \Sigma_{i=1}^{m}\frac{\mathrm{SEEC}_i}{\mathrm{U} \times \mathrm{C}_p}, \tag{2.14}$$

where m is sections between current and previous location, C_p is charger power of 350 kW, U is utilization hours.

Subsequently, road-wise peak and average charger demands ($\widehat{\mathrm{CD}}_k$ and $\overline{\mathrm{CD}}_k$) were evaluated as

$$\mathrm{CD}_k = \Sigma_{l=1}^{q}\mathrm{CD}_l, \tag{2.15}$$

where q is last charging station location.

Peak and average total charger demands ($\widehat{\mathrm{TCD}}$ and $\overline{\mathrm{TCD}}$) were obtained as:

$$\mathrm{TCD} = \Sigma_{k=1}^{r}\mathrm{CD}_k \tag{2.16}$$

6. Power demand for chargers (S.6, R.4): Peak and average power demand ($\widehat{\mathrm{P}}_l$ and $\overline{\mathrm{P}}_l$) of each selected location (l) followed by the accumulated road-wise demands ($\widehat{\mathrm{PD}}_k$ and $\overline{\mathrm{PD}}_k$) were assessed as:

$$\mathrm{P}_l = \mathrm{CD}_l \times \mathrm{C}_p, \tag{2.17}$$

$$\mathrm{PD}_k = \Sigma_{l=1}^{q}\mathrm{P}_l, \tag{2.18}$$

At the end, peak and average total power demands ($\widehat{\mathrm{TPD}}$ and $\overline{\mathrm{TPD}}$) were evaluated by aggregating the road-wise demands up to the last road (r):

$$\mathrm{TPD} = \Sigma_{k=1}^{r}\mathrm{PD}_k, \tag{2.19}$$

7. Road-wise crest factor (R.5) ($\overline{\mathrm{CF}}_k$) and energy ratio (R.6) (RER_k): Road-wise $\overline{\mathrm{CF}}_k$ was used for fine-tuning the energy ratio (RER_k) results. The CF_k accounts for all variations and outliers by computing for each section along a road, providing

a more accurate picture of energy demand variations

It was evaluated by first calculating sectional crest factor (CF_i) using equation (2.20) and then averaging the result by the total number of (n) sections of the road (see equation 2.21). For road-wise RER_k equation (2.22) was used.

$$CF_i = \frac{\widehat{SEEC}_i}{\overline{SEEC}_i} \tag{2.20}$$

$$\overline{CF}_k = \frac{\Sigma_{i=1}^{n} CF_i}{n} \tag{2.21}$$

$$RER_k = \frac{\widehat{REEC}_k}{\overline{REEC}_k} \tag{2.22}$$

III. RESULTS AND DISCUSSION

This section focuses on the detailed analysis and results obtained from applying the demand assessment model to the available data. The analysis generated a large number of data points for each section of all major roads. Plots for traffic volume, energy demand, charger quantity, and power demand for major routes were created to identify energy demand patterns for each road. Subsequently, the data points were examined using geo-spatial mapping to identify energy-demanding hotspot areas in compliance with EU regulations. This section presents these analysis results and discusses the dynamics of the various demand metrics concerning the needs of HDV charging infrastructure in Finland.

The overall required power and the daily and yearly energy demand are provided in Table 4. More detailed information per road regarding peak and average traffic volume, energy demand, charger's and power demand is presented in Fig. 5a, Fig. 5b, Fig. 5c, and Fig. 5d respectively.

The main difference between road traffic volume distribution and energy/power demand arises from road length, as longer roads such as VT4 and VT5 require more energy and charger stations to accommodate equivalent traffic volumes. Exceptions include roads such as VT3, where traffic volume consists predominantly of lower FC vehicles, such as type 2 (is observed from input data).

The energy density per kilometer can be used to identify routes such as VT4, VT6, and VT7 with high portion of most heavy HDVs, which may benefit from higher power levels of chargers. While traffic volume can indicate the number of required chargers, energy density analysis provides more detailed insights into the appropriate capacity of those chargers.

As energy, power, and number of chargers are correlated between each other for the fixed utilization time and charger's capacity, an overall analysis of average and peak demand can be provided here. While the key routes such as VT4, VT3, VT9, and VT8 should be focal points due to their substantial peak energy demands and medium RER. As such, roads with high RER like VT16, VT22, and VT21 are outliers highlighting the higher need for extra chargers compared to average number of chargers need as increase in traffic volume is more probable.

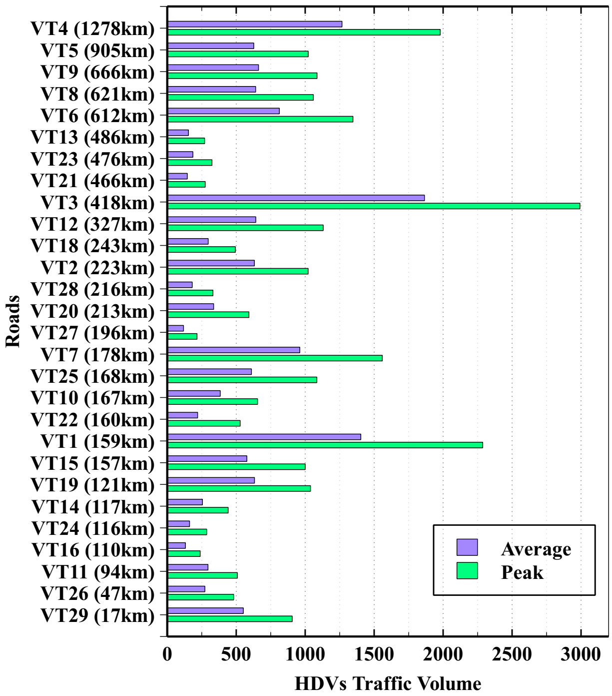
Table 4: Total energy and power demand (daily and yearly), and required number of 350-kW chargers

Total demand	Peak	Avg.
Energy [GWh/day]	13.4	8.1
Energy [TWh/year]	4.89	2.94
Power [GW]	0.614	0.371
Number of Chargers (350 kW)	1,755	1,060

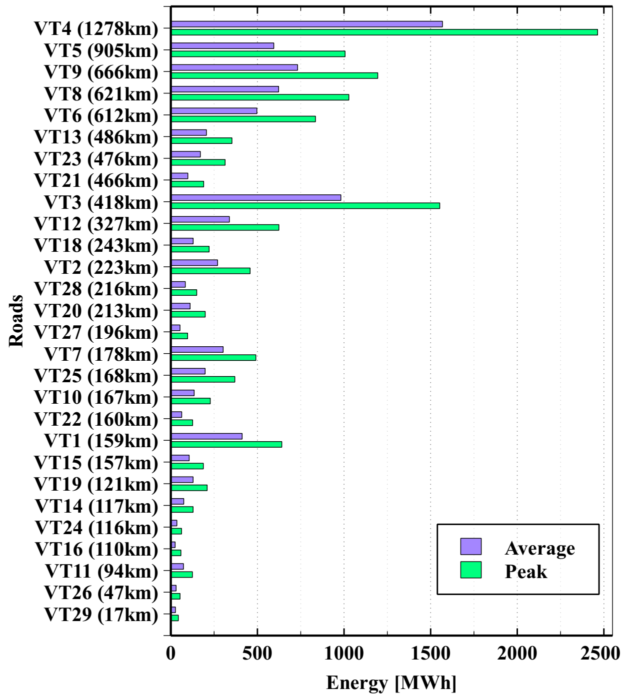
III.1. Optimizing energy outlook with the crest factor (CF)

The CF, generally calculated as the ratio of peak-to-rms of a variable, in the current case peak-to-average,can serve as an effective indicator of the variation in energy demands as represented by CF spread in Figure 6 in our case. Unlike simple road-wise ratio of peak-to-average energy demand ($RER_{k,\ at}$) as discussed earlier under section II-II.2, the $CF_{k,\ at}$ accounts for all variations and outliers by computing for each section along a road (indicated by CF spread in Figure 6), providing a more accurate picture of energy demand variations as shown in Table 5 and Figure 6. The correction percentage in Table 5, indicates the adjustment done in the $RER_{k,\ at}$ based on the $CF_{k,\ at}$ variation over the length of a road. A positive correction percentage indicates a larger energy demand buffer compared to $RER_{k,\ at}$ meaning that energy demand variation can be more substantial than RER indicates, whereas a negative correction percentage indicates the opposite.

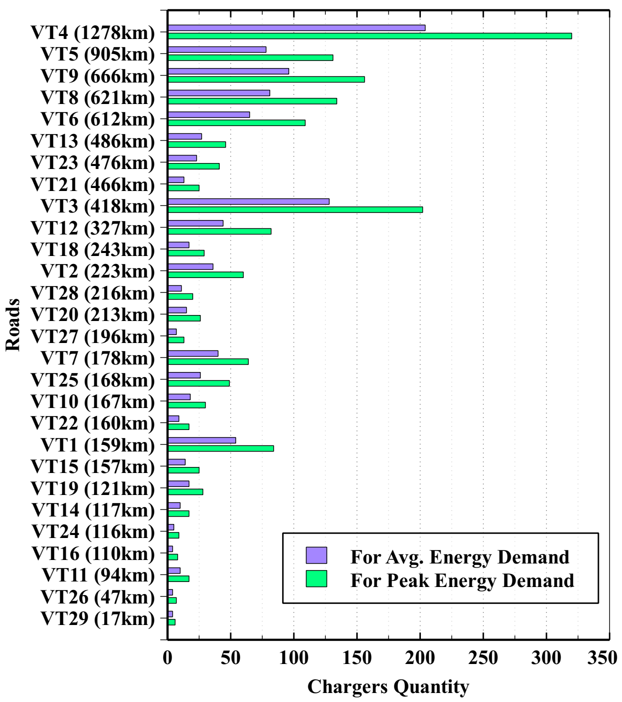
For example, VT13 has the highest CF and correction percentage, with a peak energy demand of 353 MWh significantly exceeding its average, indicating substantial variability along the road and necessitating robust infrastructure. Similarly, VT9 shows a high CF and positive correction percentage, reflecting a peak demand of 1,195 MWh, while VT22 also exhibits a high CF and correction percentage with a peak demand of 126 MWh. These roads share significant variability in



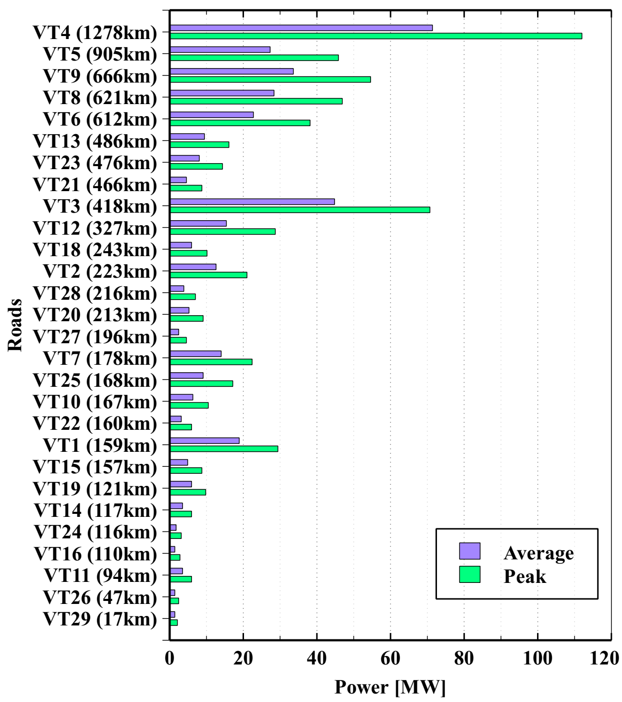
(a) Average and peak day traffic volume of HDVs evaluated for major roads in 2023.



(b) Energy demand per day evaluated on all major roads for HDVs in 2023.



(c) Fast-chargers demand (350 kW size at 22 h/day utilization) for all main roads.



(d) Power demand for 350 kW chargers at 22 h/day utilization.

Figure 5: Overview of traffic volume, energy demand, and charging infrastructure needs for HDVs in 2023.

Table 5: Road-wise energy ratio compared to average CF, VT1–VT29. Overall means average for all roads.

Road (VT)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RER	1.56	1.70	1.58	1.57	1.69	1.68	1.62	1.65	1.63	1.69	1.71	1.84	1.72	1.72	1.77
Avg. CF	1.65	1.63	1.60	1.60	1.81	1.66	1.75	1.66	2.22	1.69	1.69	1.74	2.58	1.70	1.73
Correction (%)	9	-7	2	3	11	-2	13	1	59	0	-2	-10	86	-2	-4
Road (VT)	**16**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**-**	**Overall**
RER	2.33	1.71	1.63	1.78	1.93	2.00	1.84	1.77	1.86	1.74	1.83	1.79	1.62	-	1.75
Avg. CF	1.85	1.67	1.62	1.78	1.90	2.54	1.77	1.78	1.81	1.72	1.82	1.88	1.66	-	1.80
Correction (%)	-48	-4	-1	0	-3	54	-6	1	-5	-2	-1	10	4	-	6

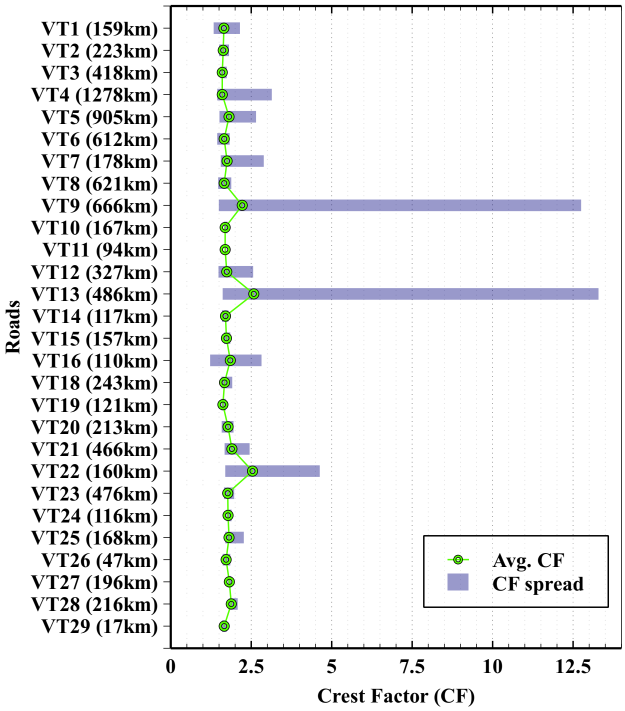


Figure 6: Crest factor evaluated for VT1–VT29 based on year 2023 data.

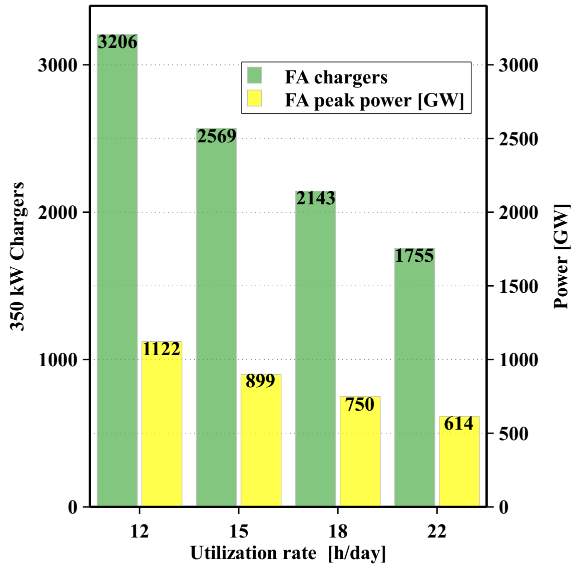


Figure 7: The impact of charger utilization rate on peak chargers and power demand.

energy demand, highlighting the need for strong infrastructure capable of accommodating such fluctuations. Based on all CF adjustments, roads VT9, VT13, and VT22 are in a higher need of over-dimensioning compared to average estimation. Thus, the CF can assist in highlighting the roads requiring more robust infrastructure.

Conversely, VT16 shows a negative correction percentage, suggesting that while its peak energy demand of 58 MWh appears high, the actual peaks over the road length might be closer to the average. With a peak power demand of 3 MW, careful infrastructure planning is necessary to avoid overestimation.

III.2. Charger utilization rate sensitivity (I.2)

Variation in a charger's daily utilization rate does not affect the energy demand estimation, as energy demand

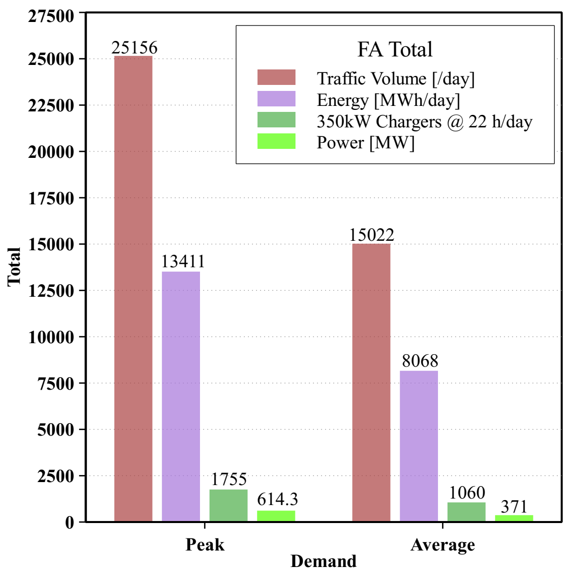


Figure 8: Daily total traffic volume and energy demand, as well as the corresponding chargers and power needs, with a focus on peak and average values for HDVs in 2023.

Table 6: Total peak energy (daily and yearly), power, and chargers demand at 22 h/day utilization for different levels of penetration.

Total Demand	100 %	75 %	50 %	25 %
DPE [GWh]	13.4	10.1	6.8	3.4
YPE [TWh]	4.89	3.70	2.47	1.23
Power [GW]	0.61	0.46	0.31	0.15
Chargers (350 kW)	1,755	1,316	878	439

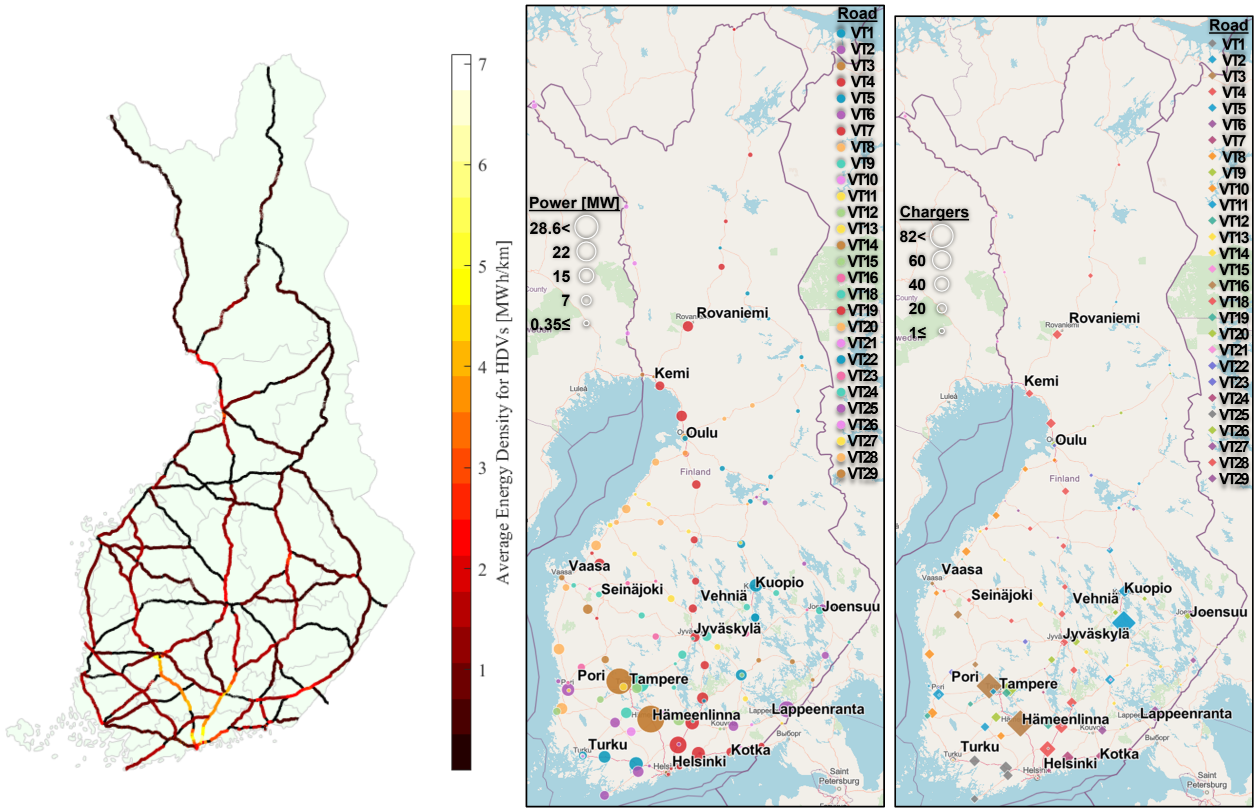
DPE: Daily peak energy; **YPE:** Yearly peak energy

is only tied to traffic volume and vehicle energy consumption. However, the variation directly impacts total peak demand estimation for power and number of chargers. Figure 7 illustrates the effect of different utilization rates—12, 15, 18, and 22 hours—on total peak demand. These rates were selected based on typical 2023 peak load duration observed in Finland during summer and winter (Fingrid, 2024).

The peak daily energy demand estimate is 13,465 MWh, indicating the need for a robust and well-distributed energy supply infrastructure. Power demand shows significant decreases as charger utilization increases: peak power demand falls from 1,122 MW at 12 hours of utilization to 614 MW at 22 hours. This trend demonstrates the benefits of spreading power loads across available chargers including reduced peak power demand, eased strain on the grid, and infrastructure development savings. As HDV electrification increases, higher utilization will further optimize grid efficiency, delaying the need for immediate grid upgrades and supporting the transition to electric vehicles.

III.3. Overview of 2023 HDVs infrastructure needs in Finland

The correlation between traffic volumes, energy demands, charger requirements, and power needs underscores the necessity for comprehensive planning of electric HDVs infrastructure in Finland. As traffic and energy demands rise, the need for more charging points, particularly 350 kW fast-chargers, increases significantly. Figure 8 provides a summary of the daily requirements for energy, charger quantity, and power across 28 roads based on available traffic volumes. The stark differences between average and peak demands offer vital insights for HDV infrastructure planning. Peak traffic volume is approximately 67 % higher than the average, highlighting the need to plan for peak conditions to avoid congestion and delays. Peak demand for energy, chargers, and power is about 66 % higher than the average, necessitating not only a robust power grid but also careful planning for energy storage and distribution. Additionally, ensuring sufficient chargers to accommodate more vehicles and prevent wait times, and a stronger power infrastructure to support these power surges during peak periods is essential. To refine infrastructure planning, different levels of electrification penetration — 100 %, 75 %, 50 %, and 25 % — were considered, as shown in table 6. For full (100 %) penetration, the yearly energy demand across all highways is estimated between 4.89–4.99 TWh, which closely aligns with 3.46 TWh (71 %–69 %) found by (Samet et al., 2021) for 91 % electrification, though this previous study did not account for vehicle type segregation. Results across these penetration levels allow planners to design scalable infrastructure as the number of electric HDVs grows. Understanding the required number of chargers and power demand also aids in estimating the capital expenditure needed for infrastructure development. Additionally, estimating yearly and daily energy demands helps forecast operational costs, including energy procurement and maintenance expenses.Those results can serve as a reference regardless of charger size, since it generally does not affect the total power and energy requirements—which are dictated by the HDV's energy consumption—only the number of chargers.



(a) Average Energy Density [MWh/km] (b) Charging stations volume [MW] (c) Number of charging stations

Figure 9: Energy density, power demand and charging stations in 2023.

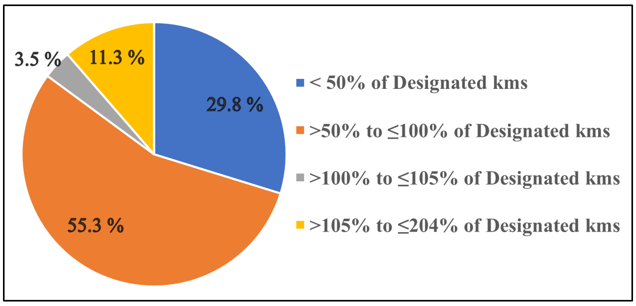


Figure 10: 142 charging stations distribution.

III.4. Geo-spatial mapping based on EU AFIR regulation

After determining energy, power, and charger requirements, the next step is geo-spatial mapping of charging stations. This involves identifying all TMS measurement points and selecting suitable locations based on EU TEN-T network criteria (represented in section II-II.1-II.1.1). The mapping includes sectional energy density (kW h/km), charger and power demand (MW), as shown in Figure 9 and explained under list entities 4, 5, and 6 of section II-II.2.

Implementing the AFIR criteria resulted in 142 charging station locations throughout Finland (see figure 10), matching exactly with the charging areas calculated by S. Wasim et al. (Shoman et al., 2023) using a shorter distance between chargers and different methodology. Each location averages 13 fast-chargers, with a maximum of 80. About 59 % of locations are within 50 to 105 % of the designated kilometers limit, nearly 30 % are below 50 %, and 11 % exceed 105 %, up to 205 %.

The energy density plot (see Figure 9a) highlights high-energy-density areas: Helsinki's adjacent regions (Porvoo, Vantaa, Espoo, Lohja, Nurmijärvi, Hirvihaara), Kotka, Lahti, Hämeenlinna, Paimio, Lappeenranta, Tampere, Jyväskylä, Kuopio, and Oulu. Medium-energy-density areas include Turku, Pori, Riihimäki, Lusi, Joensuu, Vehniä, Seinäjoki, Vaasa, Kemi, and Rovaniemi. About 63 % of points have an energy density below the average (2.43 MWh/km), while 37 % are above average.

Power demand and charging stations are plotted at the selected locations. Power demand at each location includes aggregated demands from preceding sections by HDVs. High, medium, and low energy density areas are covered with an appropriate number of chargers near demand sources (see Figures 9b and 9c).

III.5. Challenges and considerations

- Battery capacity and payload: The need for advancements in battery technology, specifically lithium metal-based batteries, is important for addressing current limitations in battery capacity and payload for long-haul HDVs. However, alternative solutions like battery-swapping could reduce the need for large battery capacities. Additionally, fast charging infrastructure, if developed sufficiently, may allow for smaller batteries, as shorter, more frequent stops could enable HDVs to cover significant distances (e.g., 300 km with an average speed of 70 km/h and a 4.5-hour driving window).

- HDVs technological improvements: Enhancements in aerodynamics and tire technology have led to notable decreases in FC. Aerodynamic drag is a primary contributor to energy consumption of HDVs, particularly at highway speeds. Tesla reports a drag coefficient (C_d) of approximately 0.36 for the Semi (InsideEVs, 2024), compared with the typical $C_d \approx 0.60$ for full-size modern tractor-trailers (approx. 36 t) (Dunn et al., Jun 19, 2000). Combined with an optimized powertrain, this design contributes to a claimed energy consumption of roughly 2 kWh/mi (equivalent to $\approx$ 1.24 kWh/km), which is not only lower than AVEEC_{FA} and AVEEC_{SA} used in this study but also substantially lower than that of most current electric HDVs on the market. This combination of lower drag, reduced per-km energy use, and rapid MegaWatt charging systems (MCS) (as discussed earlier in I) could substantially decrease operational downtime and infrastructure strain in long-haul contexts.

- Regulatory compliance: EU regulations, such as EC 561/2006 on driver rest periods, necessitate the inclusion of megawatt charging system (MCS) to reduce charging times and align with operational schedules.

- Economic considerations: Initial capital expenditure for electric HDVs remains high, though projections suggest cost parity with diesel models by 2026. Government funding and targeted investments are essential in the transitional phase.

- Policy recommendations: The results indicate the significance of strategic planning and funding in renewable energy sources, battery-electric trucks, and charging infrastructure. Finland's pursuit of carbon neutrality by 2035 heavily relies on the government's progressive subsidies and infrastructure development strategies.

IV. CONCLUSIONS

This study comprehensively analyzed the energy demand and factors influencing the placement of charging infrastructure for HDVs in Finland, in response to strict AFIR rules aimed at reducing GHG emissions. HDVs play a critical role in the road freight transport sector, contributing significantly to CO_2 emissions. As such, they are central to Finland's efforts to meet its ambitious climate goals. Although the study is focused on Finland's case, the methodology can be adapted to any country or region.

Key findings from the study carried out in this research highlight the following:

- AVEEC trends: Using the equation from Liimatainen et al. for SA in comparison with novel FA, the analysis reveals increasing AVEEC with payload but at a decreasing rate as payload goes up for FA due to advancements in vehicle design in recent years. FA is therefore more likely to accurately estimate the future energy demands of HDV charging infrastructure.

- Energy demand analysis: The 2023 peak energy demand for HDVs was 13.411 GWh on peak days, significantly higher than the average daily demand of 8.162 GWh. This disparity highlights the need for infrastructure capable of handling peak loads, with an annual peak energy demand of 4.89 TWh (2.94 TWh average demand).

- Charger and power requirements: Increasing the charger utilization from 12 to 22 hours/day significantly reduces both charger numbers and peak power demand, while energy demand remains stable. At 22 hours/day utilization with 100% penetration, around 1,755 chargers (350 kW each) are needed with peak power demands of 0.61 GW. Optimizing charger utilization cuts charger numbers by 45% and reduces peak power demand against 2023 traffic volumes for HDVs, making it one of the key factor for minimizing infrastructure costs, reducing grid strain, and ensuring a smooth transition to zero-emission HDV fleets.

- Spatial distribution of charging stations: High-energy-density areas such as Helsinki, Lahti, and Tampere among others were identified as priorities for infrastructure development. The spatial analysis ensures basic compliance with EU regulations and strategic placement for better efficiency. The proposed placement of charging stations can be further optimized by considering multiple factors in conjunction:

- EU regulations compliance: Ensuring the minimum power requirement is also complied for charging stations.
- Grid connection proximity: Choosing locations with available grid access for efficient energy supply.
- Overlap identification: Identifying common locations for overlapping highway areas to minimize the number of stations.
- Socio-economic viability: Preferring locations near existing facilities and highway interchanges for better accessibility.

To summarize, the shift to electric HDV transportation comes with both significant hurdles and advantages. Precise fuel usage prediction, strategic positioning of charging stations, and ongoing technological progress are necessary to decrease emissions and achieve regulatory goals. Policymakers and stakeholders should use this information to make data-driven decisions, improve charging infrastructure and guarantee effective energy distribution to meet the increasing need for HDV electrification in Finland. The obtained information can be further used for analysis of the local grid strength and assess the potential for participation in frequency support markets.

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