Technology Data

Commercial freight- and passenger transport

Energistyrelsen
Danish Energy Agency

Technology descriptions and projections for long-term energy system planning

Technology data – Commercial freight- and passenger transport

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Amendment sheet

Publication date

Publication date for this catalogue "Technology Data – Commercial freight- and passenger transport" is May 2023. In September 2023 this amendment sheet has been added and also the possibility to add descriptions of amendments in the individual chapters if required. Hereby the catalogue can be updated continuously as technologies evolve, if the data changes significantly or if errors are found.

The newest version of the catalogue will always be available from the Danish Energy Agency's website.

Amendments after publication date

All updates made after the publication date will be listed in the amendment sheet below.

Version	Date	Ref.	Description
001	September 2023	Datasheets	Datasheets adjusted and removed from the technology catalogue. Datasheets in xlsx format remain available on the website.
002	March 2024	Datasheets	Error in datasheets corrected. Values for CO_2-emissions on long haul driving (typical payload) incorrectly showed the values of empty payloads. Furthermore an emission factor for diesel of 74.6 gCO2/MJ replaces the previous value of 69.6 gCO2/MJ.

Preface

The purpose of this report is to provide a comprehensive overview of three key transport technologies within the trucking and passenger bus industries: internal combustion engines, battery electric and fuel cell electric.

Technology catalogues published by the Danish Energy Agency aims to establish a standardized and up-to-date basis for planning activities, including evaluations of environmental impacts, technical and economic analyses, and assessments of framework conditions for the development and deployment of specific classes of technologies. It should be noted that this report does not aim to provide an exhaustive collection of specifications on all available incarnations of transport technologies. Instead, selected, representative technologies are included to enable generic comparisons of technologies with similar functions in the transport system.

Updates to this report will can be made as technologies evolve, significant data changes occur, or errors are found. Any updates will be listed in the amendment sheet on and in connection with the relevant chapters. The most recent version of this report will is available on the Danish Energy Agency's website.

Finally, this report is intended for both Danish and international audiences and aims to contribute to similar initiatives aimed at forming a public and concerted knowledge base for international analyses.

Danish preface

Formålet med denne rapport er at give et indblik i tre centrale transportteknologier inden for lastbiler og passagerbusser: Forbrændingsmotorer, batterielektriske og brændselscelleelektriske.

Teknologikataloger udgivet af Energistyrelsen har til formål at etablere et standardiseret og opdateret grundlag for planlægningsarbejde og vurderinger af forsyningssikkerhed, beredskab, miljø og markedsudvikling hos bl.a. de systemansvarlige selskaber, universiteterne, rådgivere og Energistyrelsen. Dette omfatter for eksempel fremskrivninger, scenarieanalyser og teknisk-økonomiske analyser. Det skal bemærkes, at denne rapport ikke har til formål at give en udtømmende samling af specifikationer for alle tilgængelige transportteknologier. I stedet indgår udvalgte, repræsentative teknologier for at muliggøre generiske sammenligninger af teknologier med lignende funktioner i transportsystemet.

Opdateringer til denne rapport vil blive foretaget i takt med, at teknologier udvikler sig, der sker væsentlige dataændringer, eller der bliver fundet fejl. Eventuelle opdateringer vil blive anført i ændringsarket. Den seneste version af denne rapport vil være tilgængelig på Energistyrelsens hjemmeside.

Endelig henvender denne rapport sig til både dansk og internationalt publikum og har til formål at bidrage til lignende initiativer, der har til formål at danne et offentligt og fælles vidensgrundlag for internationale analyser.

Table of Contents

1. Introduction

This catalogue presents technologies applying to on-road Heavy Duty Vehicles (HDV), more specifically, trucks and buses with a maximum authorized weight of more than 3.5 tons[1]. Heavy duty vehicles, in particular trucks, have a high degree of diversity, i.e., they present a wide variety of different applications, requirements and driving patterns.

The primary purpose of the catalogue is to provide generalized data that can be applied in analyses of HDVs in the road transport sector, including economic scenario models and transport planning. The focus of the catalogue is limited to providing data for the technological performance of the vehicles. Consequently, the catalogue does not provide data or detailed information on fuel prices, any upstream emissions associated with fuel production, or costs and externalities linked to the necessary infrastructure.

Each technology is described in a separate technology chapter, making up the main part of the catalogue. This first version of the catalogue on HDV will focus on technologies involving battery electric and fuel cell powertrains. This first version will therefore not include other technologies such as gas, methanol, or other powertrain alternatives. This is partly because such data and experience already exist and partly due to the resources allocated to conduct this study. It is however the intention that the catalogue be extended with additional chapters and technologies when relevant. It is not the intent of the catalogue to choose or recommend any specific technologies, but strictly to provide descriptions alongside data for use in further analyses and modelling of the transport sector.

The catalogue also includes a chapter on the conventional Internal Combustion Engines (ICE) which serves as the baseline to which new HDV technologies are compared. The baseline fuel is European market diesel B7. Each technology is described in relation to powertrain, typical fuel/energy consumption, vehicle weights, driving range, and upfront, operations, and maintenance costs. The technology chapters contain both a qualitative description of the technologies and a quantitative part including a table with the most important technology data. All aspects and data within the catalogue are related to new vehicles. Quantitative data is published in separate Excel file for Data sheets.

The various fueling systems (i.e., fueling stations, electric charging, etc.) are described in the catalogue, including the status and expectations for future development, but quantitative information regarding fueling is not included in the datasheets. Comprehensive total cost of ownership calculations or economic scenario analyses can be undertaken by combining fuel and charging cost inputs from other sources with the data found within this catalogue.

The qualitative and quantitative descriptions below explain the formats of the technology chapters, how data are obtained, and the underlying assumptions.

To undertake meaningful analysis of technologies in the HDV segment of transport, it is important to understand the complexity of tasks involving HDV transport. However, in both the truck and bus category it is necessary to consider, measure and evaluate the new technologies within a simplified segmentation according to e.g., configuration, weight, range, and power. As a background for defining and evaluating each technology, an analysis of segmentations has been made (Annex 1 – Segmentation analysis). This analysis covers HDV segments in Denmark based on vehicle weight, while truck segments also considered the truck/trailer combination. The analysis segmentation was primarily based on available data on the amount of transport work undertaken, the number of HDVs, the composition of the vehicle fleet and driving patterns, and inputs from relevant stakeholders. Based on the complexity of the segmentation in the analysis

[1] The catalogue focuses on the heavier segments e.g. trucks above 12 tons and only full size buses. This means that the smaller type of HDV vehicles, technically more similar to vans, are not included in neither the descriptions nor the data sheets.

the technology chapters will be directed towards a more simplified split into 3 segments for trucks and 2 segments for buses. Part of the data are however presented in ranges covering e.g., a wider range of weights. In this way, the segmentation analysis in Annex 1 serves primarily as a context and background for qualitative considerations for the authors of each technology chapter in the evaluation of the different technologies' specifications.

Technologies included in the catalogue:

- Conventional Internal Combustion (ICE) Vehicles (diesel)
- Battery Electric Vehicles (BEV)
- Fuel Cell Vehicles (FCV)

BEV and FCV technologies are chosen since commercial experience and consistent data availability for these are still relatively limited combined with that these technologies are of increasing relevance for studies on the transport sector. Depending on the demand for new data on powertrain technologies, the technology chapters may later be expanded, or new chapters included in the catalogue. The selection of these technologies, and the level of detail required, could be arrived via consultation with the Danish Energy Agency. Examples of such potential technologies could be gas or methanol vehicles.

The included segments are the following.

Trucks:

- Solo truck up to 26 tons (28 tons for electric and fuel cell trucks)
- Truck with trailer up to 56 tons (60 tons for future EMS[2] road trains)
- Semi-trailer truck up to 50 tons (60 tons for future EMS road trains)

Buses

- Route traffic/City >12 meters in length
- Tourist/Coach >12 tons

1.1. Qualitative description

The qualitative description describes the key characteristics of the technology as concise as possible. The following paragraphs are included where relevant for the technology.

Contact information

Containing the following information:

- Contact information: Contact details in case the reader has clarifying questions to the technology chapters. This could be the Danish Energy Agency or the author of the technology chapters.
- Author: Entity/person responsible for preparing the technology chapters
- Reviewer: Entity/person responsible for reviewing the technology chapters.

2 EMS = European Modular System

Description of drivetrain technology

Presentation of the drivetrain technology for non-engineers. A picture of a representative vehicle as well as a basic diagram of the drivetrain technology should be included. In this qualitative section the technology description should include the current driving range and maximum vehicle weight of the technology, and the expected development in these parameters.

This section should also contain a description of the expected most relevant applications in Denmark based on the statistics. This qualitative consideration could include elements from the segmentation analysis in annex 1 and within the most relevant vehicle segments describe aspects as the number of vehicles, vehicle sizes, carrying capacity, typical driving patterns, e.g.

It should be noted, that in the quantitative parts of the catalogue and in the coherent datasheets the technologies should be evaluated within the following segments:

Trucks:

- Solo truck up to 26 tons (28 tons for electric and fuel cell trucks)
- Truck with trailer up to 56 tons (60 tons for future EMS[3] road trains)
- Semi-trailer truck up to 50 tons (60 tons for future EMS road trains)

Buses

- Route traffic/City >12 meters in length
- Tourist/Coach >12 tons

Advantages/disadvantages

A description of specific advantages and disadvantages relative to the other drivetrain technologies.

Fuelling or charging system

A description of the fuelling or charging system should provide an overview of the current status (i.e., number of fuelling/charging stations in Denmark today), prospects for development going forward, and potential benefits and/or challenges relative to other drivetrain technologies.

In relation to electric vehicles this also includes a description of electric road systems (overhead power lines, ground level power through rail or induction) and their possible effect on the performance and specifications of electric vehicles.

Interaction with the energy system

Briefly reflect on how the drivetrain technology and/or the fuel utilised interacts with the Danish energy system. I.e., rapid charging of large fleets of heavy transport vehicles may strain the distribution network in some areas, but electric or hydrogen vehicles could potentially also provide ancillary services (i.e., vehicle to grid services).

Current market and technological status and future development perspectives

A presentation of the current market and technology status, and expectations for the future. This section should include the most relevant challenges to further development of the drivetrain technology. The potential for technological development in terms of costs and efficiency should be quantified in the data sheets.

The status and developments in neighbouring countries shall also be discussed (i.e., developments in hydrogen or gas fuelling, rapid charging stations and/or E-roads that would influence international transport in Denmark).

3 EMS = European Modular System

Environment and climate

The environmental footprints associated with heavy duty vehicles arise largely during their use and via their production and scrapping.

This section should therefore include a description of the energy use, technological filters utilised, and resulting "tailpipe" or *local emissions*[4] released during use of the specific drivetrain. Local emissions include CO_2, CH_4, NO_X, N_2O, SO_2 and particulate emissions per km.

In addition, the section should include a description of where the future vehicles in Denmark are likely to be produced and provide a rough estimate (and/or range) of the upstream CO_2 emissions associated with the production and scrapping/recycling of the vehicle. Given the range of CO_2 intensities related to battery production, this is likely to be a relevant parameter going forward.

The above sets of values should be included in the datasheets in the quantitative section, and when combined with data on emission intensity of fuels (from other DEA sources), allow for a life-cycle assessment of the technology.

Prediction of performance and costs

Cost reductions and performance improvements can be expected for most technologies in the future, and particularly battery/hydrogen electric drivetrains. This section describes the assumptions underlying the cost and performance aspects in 2022 as well as the improvements assumed for the years 2025, 2030, 2040 and 2050.

The specific drivetrain technology is identified and classified in one of four categories of technological maturity (see below), indicating the commercial and technological progress, and the assumptions for the projections are described in detail.

Predicting the future costs of technologies may be done by applying a cost decomposition strategy, i.e., decomposing the costs of the technology into categories such as labour, materials, etc. for which predictions already exist. Alternatively, the development could be predicted using learning curves. Learning curves express the idea that each time a unit of a particular technology is produced, learning accumulates, which leads to cheaper production of the next unit of that technology. The learning rates also take into account benefits from economy of scale and benefits related to using automated production processes at high production volumes.

The potential for improving technologies is linked to the level of technological maturity. The technologies are categorised within one of the following four levels of technological maturity.

<u>Category 1</u>. Technologies that are still in the *research and development phase*. The uncertainty related to price and performance today and in the future is highly significant.

<u>Category 2</u>. Technologies in the *pioneer phase*. The technology has been proven to work through demonstration. Due to the limited application, the price and performance is still attached with high uncertainty, since development and customisation is still needed. The technology still has a significant development potential.

<u>Category 3</u>. *Commercial technologies with moderate deployment*. The price and performance of the technology today is well known. These technologies are deemed to have a certain development potential and therefore there is a considerable level of uncertainty related to future price and performance.

<u>Category 4</u>. *Commercial technologies, with large deployment*. The price and performance of the technology today is well known, and normally only incremental improvements would be expected. Therefore, the future price and performance may also be projected with a relatively high level of certainty.

[4] It is not necessary to include upstream emissions. Calculations of local emissions will require assumptions regarding CO_2 contents of fuels that can be found in the DEA's Socio-economic calculation assumptions (Samfundsøkonomiske beregningsforudsætninger).

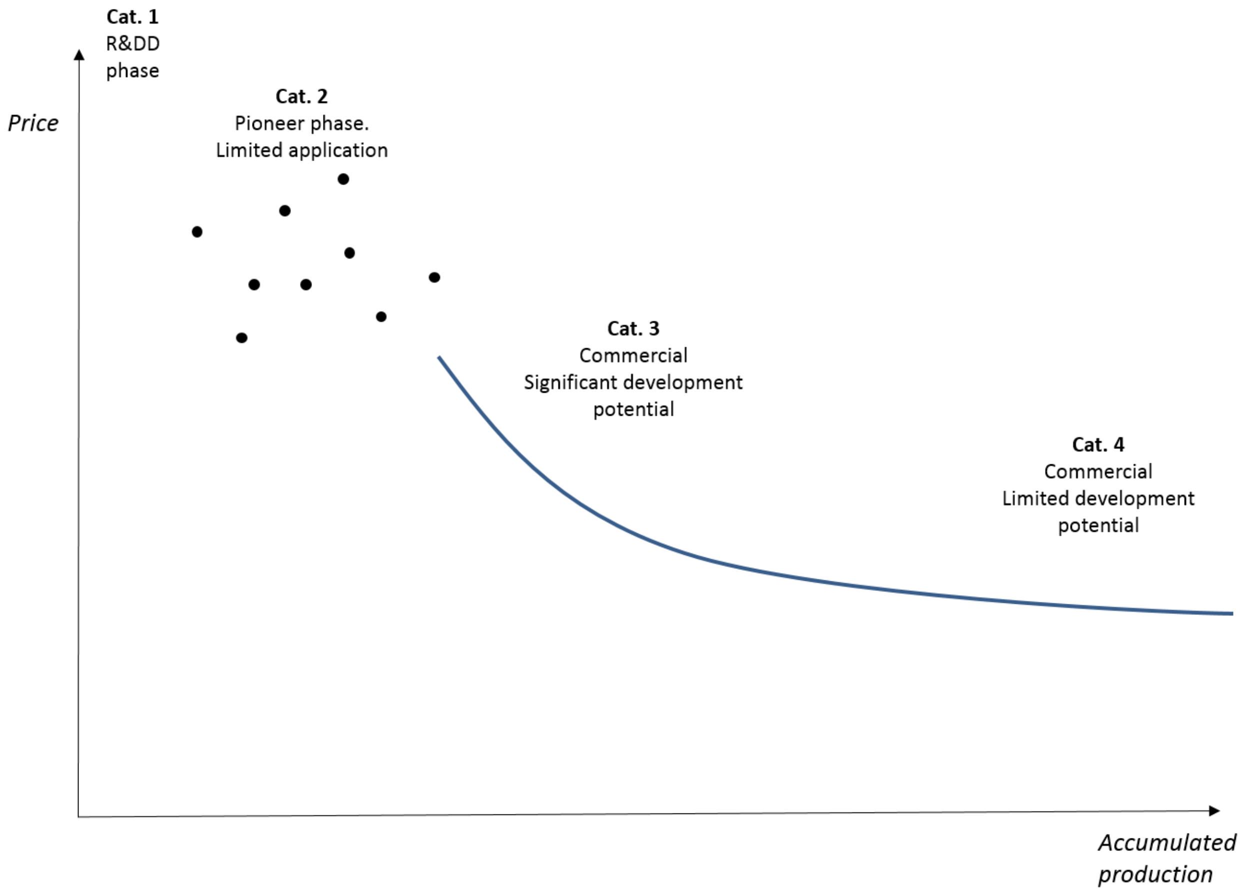

Figure 1: Technological development phases. Correlation between accumulated production volume (MW) and price

Uncertainty

The catalogue covers both mature technologies and technologies under development. This implies that the price and performance of some technologies may be estimated with a relatively high level of certainty whereas in the case of others, both cost and performance today as well as in the future are associated with high levels of uncertainty.

This section of the technology chapters explains the main challenges to precision of the data and identifies the areas on which the uncertainty ranges in the quantitative description are based. This includes technological or market related issues of the specific technology as well as the level of experience and knowledge in the sector and possible limitations on raw materials. The issues should also relate to the technological development maturity as discussed above.

The level of uncertainty is illustrated by providing a lower and higher bound beside the central estimate, which shall be interpreted as representing probabilities corresponding to a 90% confidence interval. It should be noted, that projecting costs of technologies far into the future is a task associated with very large uncertainties. Thus, depending on the technological maturity expressed and the period considered, the confidence interval may be very large. It is the case, for example, of less developed technologies (category 1 and 2) and long-time horizons (2050).

Additional remarks

This section includes other information, for example links to web sites that describe the technology further or give key figures on it.

1.2. Quantitative description

To allow for comparison of different drivetrain technologies, it is important that the data is presented in such a way that the utility of each set of combination of technology and vehicle segment is as comparable as possible. For example, if the battery in an electric truck-semi ≤50t results in that truck/trailer combination weighing more than a diesel version within the same category, the emissions and energy usage should be provided for a diesel and electric truck with the same amount of payload.

A table designed to contain all the required quantitate data is displayed below. All data should refer to a new vehicle produced in the year indicated. All cost data should be stated in fixed 2022 prices excluding value added taxes (VAT) and other taxes.

Each cell should contain only one central value (i.e., no range of values). To reflect a potential range of values, there are columns labelled "uncertainty". The level of uncertainty is illustrated by providing a lower and higher bound. These are chosen to reflect the uncertainties of the best projections by the authors. The section on uncertainty in the qualitative description for each technology indicates the main issues influencing the uncertainty related to the specific technology. For technologies in the early stages of technological development or technologies especially prone to variations of cost and performance data, the bounds expressing the confidence interval could result in large intervals. The uncertainty only applies to the market standard technology; in other words, the uncertainty interval does not represent the product range (for example a product with lower efficiency at a lower price or vice versa). The level of uncertainty is stated for the most critical figures such as investment cost and efficiencies. Other figures are considered if relevant.

All data in the tables should be referenced by a number in the utmost right column (Ref), referring to source specifics below the table.

Notes can include additional information on how data was obtained, as well as assumptions and potential calculations behind the figures presented.

Vehicle segment & subcategory	**Heavy road transport vehicles**												
	2021	**2025**	**2030**	**2040**	**2050**	**2025**	**2025**	**2030**	**2030**	**2050**	**2050**	**Note**	**Ref**
Technical parameters	**ctrl**	**ctrl**	**ctrl**	**ctrl**	**ctrl**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**		
Maximum payload [kg]/# of passengers													
Vehicle mass in running order [kg]													
Vehicle maximum gross weight [kg]													
Typical payload [kg]/# of passengers													
Fuel tank size [litres]													
Weight of battery [kg]													
Charging capacity [kW]													
Typical refuelling time [minutes]													
Number of axles – max													
Number of axles – typical													
Motor size [kW]													
Vehicle length – max [m]													
Vehicle length – typical [m]													
Energy/technical data													
Powertrain efficiency [%]													

- Urban delivery													
- Regional distribution													
- Long haul													
Fuel energy – mass in running order [MJ/km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Fuel energy - maximum gross weight [MJ/km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Fuel energy - typical load [MJ/km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Vehicle Range – mass in running order [km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Vehicle Range – maximum gross weight [km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Vehicle Range - typical load [km]													
- Urban delivery													
- Regional distribution													
- Long haul													
Environment													
Urban													
- CO_2 emissions - [g/km]													
- CH_4 emissions - [g/km]													
- NOX emissions - [g/km]													
- N_2O emissions - [g/km]													
- SO_2 emissions - [g/km]													
Rural													
- CO_2 emissions - [g/km]													
- CH_4 emissions - [g/km]													
- NOX emissions - [g/km]													

- N_2O emissions - [g/km]													
- SO_2 emissions [g/km]													
Highway													
- CO_2 emissions - typical load [g/km]													
- CH_4 emissions - [g/km]													
- NO_X emissions - [g/km]													
- N_2O emissions - [g/km]													
- SO_2 emissions - [g/km]													
Net CO_2 emissions from production and recycling of vehicle [ton]													
Financial data													
Typical vehicle lifetime [years]													
Typical battery Fuelcell lifetime [years]													
Typical vehicle lifetime [km]													
Typical # of km driven during first year [km]													
Upfront vehicle cost [€]													
- Cost of 24V battery													
- Cost of Powertrain													
Fixed maintenance cost [€/year]													
Variable maintenance cost [€/km]													

Some parameters are not linked to an actual uncertainty, and therefore it is more suitable to present a range of values that represent the vehicle segment, while other parameters are connected to an uncertainty that needs to be presented.

Technical parameters

Maximum vehicle payload/number of passengers

For solo truck and truck/semi, truck/trailer segments and drivetrains the maximum payload in kg. For buses, the maximum number of passengers.

Mass in running order

For all drivetrain-segment combinations, the mass in running order means the mass of the vehicle with its fuel tank(s) filled to at least 90 % of its or their capacity/ies, including the mass of the driver, of the fuel and liquids, fitted with the standard equipment in accordance with the manufacturer's specifications and, when they are fitted, the mass of the bodywork, the cabin, the coupling and the spare wheel(s) as well as the tools.

Vehicle maximum gross weight

For all drivetrain-segment combinations, the maximum total allowed operating weight of the vehicle and trailer(s) in kg. This should take into consideration any differences according to drivetrain. For example, legislation that allows for particular drivetrain types to have a larger maximum weight in order to maintain the same payload as conventional drivetrains.

Vehicle weight - with typical load (kg)/# of passengers

For all drivetrain-segment combinations, the total weight of the vehicle and trailer(s) in kg for what has been deemed to be the typical or average usage for a new vehicle of this segment.

Fuel tank and/or battery size

Size of the fuel tank (in litres), or capacity of a BEV's and FCV's battery (in kWh). For batteries, it is the total battery capacity. The majority of electric vehicles do not allow for utilisation of 100% of the battery, but this aspect will be reflected in the vehicle range.

Charging capacity

Only relevant for electric vehicles.

Typical charging/refuelling time

This not only depends on the onboard vehicle technology but also needs considerations of the development in charging/refuelling infrastructure.

Number of axles – max

Maximum number of axels for the vehicle.

Number of axles – typical

Standard number of axels for the typical vehicle.

Motor size (kW)

Size of the motor in a standard vehicle within this subcategory (in kW).

Vehicle length – max

The maximum length of the bus, solo truck, or truck and trailer (m).

Vehicle length – typical

The length of the typical bus, solo truck, or truck and trailer in this subcategory (m).

Energy and fuel related parameters

Energy consumption

The energy consumption (MJ/km) should ideally be based on examples of vehicles under typical Danish conditions analysed with driving simulation software (or results herefrom) preferably following international standards for emissions and energy use calculations. The results from these simulations should if possible also be summarised in a chart describing each chosen vehicle type with weight on the horizontal axis and energy consumption (MJ/km) on the second axis, with each vehicle type depicted as a dataseries with three points signifying the three weights (empty, typical, maximum) analysed. Both gross energy use (from tank) and net energy use (at wheel) should be illustrated in the charts / tables. Energy consumption (in MJ/km) for the three defined weights:

- Vehicle mass in running order
- Vehicle maximum gross weight

- Typical load/# of passengers

The values should be presented according to urban, rural and highway driving.

Vehicle Range

Vehicle range (in km) for the subcategory of vehicles for the two defined weights:

- Vehicle mass in running order
- Vehicle maximum gross weight

As for the energy consumption values, the values should be presented according to urban, rural and highway driving and for BEV only the sustainable use of the battery (20-90 pct. State of charge). If there are noticeable seasonal variations in vehicle range (i.e., batteries having lower capacities in winter), these should be reflected upon.

Environment

Emissions

Local emissions of CO_2, CH_4, N_2O, NO_x and SO_2 in g/km resulting from the operation of the vehicle for the two defined weights above:

- Vehicle maximum gross weight
- Typical load/# of passengers

Upstream emissions related to fuels are not included.

Net CO_2 emissions from production and recycling of vehicle

To assist in undertaking LCA analysis, an estimate of the CO_2 emissions attributed to the production, and eventual scrapping, of the vehicle should be included. If a portion of the vehicle can be recycled, then the CO_2 emission savings related to this shall be deducted.

Financial data

Typical vehicle lifetime

Typical lifetime of the vehicle (in years)

Typical battery lifetime

Typical lifetime of the battery/fuel cell (in years). Depends on assumptions on charging cycles etc.

Typical vehicle lifetime

Typical lifetime of the vehicle (in km)

Typical # of km driven

Typical # of km driven as an average of first four years of ownership.

Upfront vehicle cost

The upfront cost of the typical vehicle (in €). Cost of batteries/fuel cell/drivetrain should be presented separately. If a significant replacement part (i.e., a battery) is anticipated to be required before the end of the vehicle's typical lifetime, then the additional anticipated cost of that part in a future year should be indicated as a potential extra cost.

Fixed O&M

The fixed operations and maintenance O&M costs (average during the first 4 years (€/year)).

Variable O&M (€/km)

The variable operations and maintenance O&M costs (average during the first 4 years year (€/km)).

2. Qualitative description – Internal combustion engine vehicles

Contact information

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- Author: Danish Technological Institute, Kim Winther, kwi@dti.dk
- Reviewer: The Danish Energy Agency

Description of powertrain technology

Most HDVs today are driven by diesel engines. The diesel truck was first introduced in 1923 whereas diesel fuel became mainstream in the 1930's. From the beginning, fuel efficiency and durability of the diesel trucks were superior to their gasoline counterparts.

The diesel engine is very versatile and can therefore serve in any vehicle segment. Due to the high energy density of diesel fuel, this includes vehicles with hoist or cooling systems, which can place additional space and/or energy demands on the vehicle.

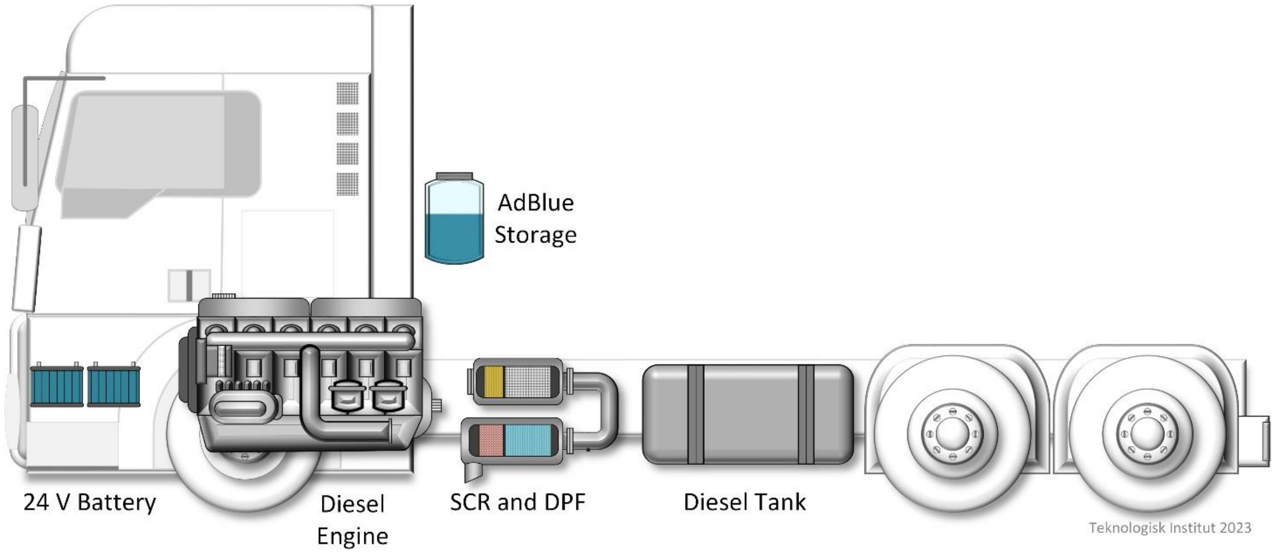

Figure 2 Basic diagram of the diesel powertrain

Heavy duty diesel engines are typically 6- or 8-cylinder turbo diesel combustion engines with particulate filter (DPF) and a reduction catalyst (SCR) for lower urban emissions. The engines can use ultra-low-sulfur diesel, synthetic diesel made with GTL (Gas-to-Liquid) or PtX (Power-to-X) technology, or biodiesel. Special ethanol versions are also available. Some variants use a spark ignition engine instead of a diesel which has compression ignition. This is true for methanol and natural gas/biogas whether it is used in the compressed or liquefied state.

This technology catalogue does not include hybrid ICE vehicles, which means that there is no regenerative braking on the vehicles simulated in this report. The reason behind this is to secure a baseline that mirrors the baseline as seen in the sector today. However, future developments within ICE trucks may well prove that regenerative breaking and hybrid solutions in general might play a significantly larger role. If these technologies become more relevant, the catalogue might be revisited to include these.

Advantages/disadvantages

The advantage of the ICE vehicle is mainly it being a highly refined, proven and well understood technology. It is highly scalable, many versions are available, and there is good access to service and repairs. ICE's can also operate in extreme climate conditions without loss of performance.

Due to the high energy density of diesel fuel, the range is long and can easily be extended with extra fuel tanks. ICE's have some degree of fuel flexibility. However, the fuels that are widely available today are mostly fossil fuels, which inherently increases their negative impacts on climate change through greenhouse gas emissions.

Combustion engines can deliver high power output for extended periods of time. Due to high volume production, production costs are low. Safety is good (high flashpoint, no sparks), up-time is high, but acceleration capability limited.

Because ICE's only work efficiently in a narrow band of engine speeds, heavy ICE vehicles require many gears. Even though modern gear boxes do not require manual shifting, the gears do add complexity and weight to the powertrain.

The ICE requires engine oil which must be changed at regular intervals. Used engine oil is regarded as toxic waste. Another disadvantage is the exhaust gases which are obliged to be cleaned through an advanced system of filters and catalysts to obtain legal levels. These necessary systems add costs and complexity to newer vehicles compared to older types. These systems also require a urea-based reactant (commercial name AdBlue) to function, an extra cost, and a minor inconvenience for the driver to fill up the tank. Typical consumption of AdBlue is 4-6% of the diesel fuel consumption (Yara, 2023).

Fueling or charging system

Fueling a diesel truck is uncomplicated and refueling points are plentiful all over Europe. Alternative diesel fuel, such as unblended biodiesel, is only available at a limited number of fuel stations in Denmark. In Denmark, biogas is available at 22 stations.

Interaction with the energy system

Diesel fuel is almost entirely fossil based and fossil oil comes mostly from imports. Although ICE vehicles are also capable of using a variety of biofuels or e-fuels, these fuels are expected to be in high demand from other sectors that are harder to abate such as aviation, shipping, and industry.

Current market and technological status and future development perspectives

Diesel engines are by far the most dominant form of propulsion technology for trucking today, and despite many efforts in Europe and USA to promote alternative powertrains, diesel technology is expected to dominate the global trucking industry at least until 2050 (IEA, Energy Technology Perspectives, 2020).

Being a Category 4 technology (Figure 1), the potential for technological development is somewhat limited. However, advancements ICE powertrains are continuously being developed to improve efficiency in their use.

Technical improvements such as hybridization of ICE powertrains are expected to contribute to decarbonization in the near term, while biofuels are expected to play a growing role from the 2030's on. In the longer term, a complete shift away from carbon-based fuels is necessary (IEA, Energy Technology Perspectives, 2020).

Hydrogen combustion diesel-type engines are under development (Cummins, 2022). How well this alternative technology will compete economically with FCEV is difficult to predict at the current state of development.

Environment and climate

Modern ICE vehicles are equipped with filters and catalysts, reducing air pollution, including particulate matter, to the legal levels. Since diesel fuel in the EU is almost 100% sulfur free the SO_X emission is negligible. Particulate matter not only comes from engine combustion but also from tire wear and the vehicles brake system. It would be cumbersome trying to determine these sources meaningful at vehicle level, and it is not within the scope of this catalogue with its focus on energy efficiencies. From a climate perspective, current EU Road diesel fuel is a blend of 7% biodiesel and 93% light fossil gas oil, leading to high specific CO_2 emissions. Alternative ICE fuels, such as e-fuels and biodiesel, are only available in limited quantities, at high cost, and with varying CO_2 reduction impact.

The CO_2 footprint from vehicle production and recycling comes mainly from production of raw materials (steel etc.).

Engine noise from ICE vehicles can be a significant issue especially in urban areas. This can be reduced with hybrid and/or gas powertrains.

Prediction of performance and costs

The cost of diesel and other ICE powertrains are expected to remain largely constant in the future (Carlier, 2022).

However, from 2025 there will be a new CO_2-based Road tax for trucks above 12 tons in Denmark. It will impact diesel trucks and buses with about 1 DKK/km. The purpose of this tax is to limit the use of diesel trucks and promote purchases of electric trucks (Andersen, 2022).

The technical limits of future truck performance are explored in the USA-based SuperTruck program (Singh, 2014) which showcases a combination of several advanced technologies for future trucks.

The main predictions related to ICE are.

- Engine peak efficiencies are expected to rise from the current 40-45 % to about 60%
- Hybrid powertrains will improve especially the city-driving efficiency.

Uncertainty

The data for diesel trucks are quite certain. This in part because of the truck manufacturers test their products in real life situations. Independent entities such as ICCT and IEA have also delivered comprehensive test data for trucks through the years. The economy of trucks is quite transparent due to a well-established leasing market where all the fixed costs of ownership are accounted for. It is estimated that 25% of new ICE trucks in Denmark are currently leased.

Additional remarks

The ICE technology has been dominant for many decades, and it will expectedly take several years for alternative power trains to occupy a significant share of the total HDV fleet. However, it is expected that the fossil fuels in transport have to be phased out, in order to reach set climate targets. Consequently, new policies might induce new restrictions to enhance competitiveness of non-fossil alternatives.

2.1. Solo Truck < 26 tons

A solo truck is a traditional rigid truck without a trailer. It can be configured for general cargo, refrigerated goods (reefer) or bulk transport, with a flat bed, a tilting tray, or a crane. Maximum vehicle weight according to EU legislation is 26 tons, and the expected development is that this will be raised at least for 4-axle versions (Danish Transport Ministry, 2022).

Figure 3 Picture of a representative vehicle (Volvo Danmark, 2023)

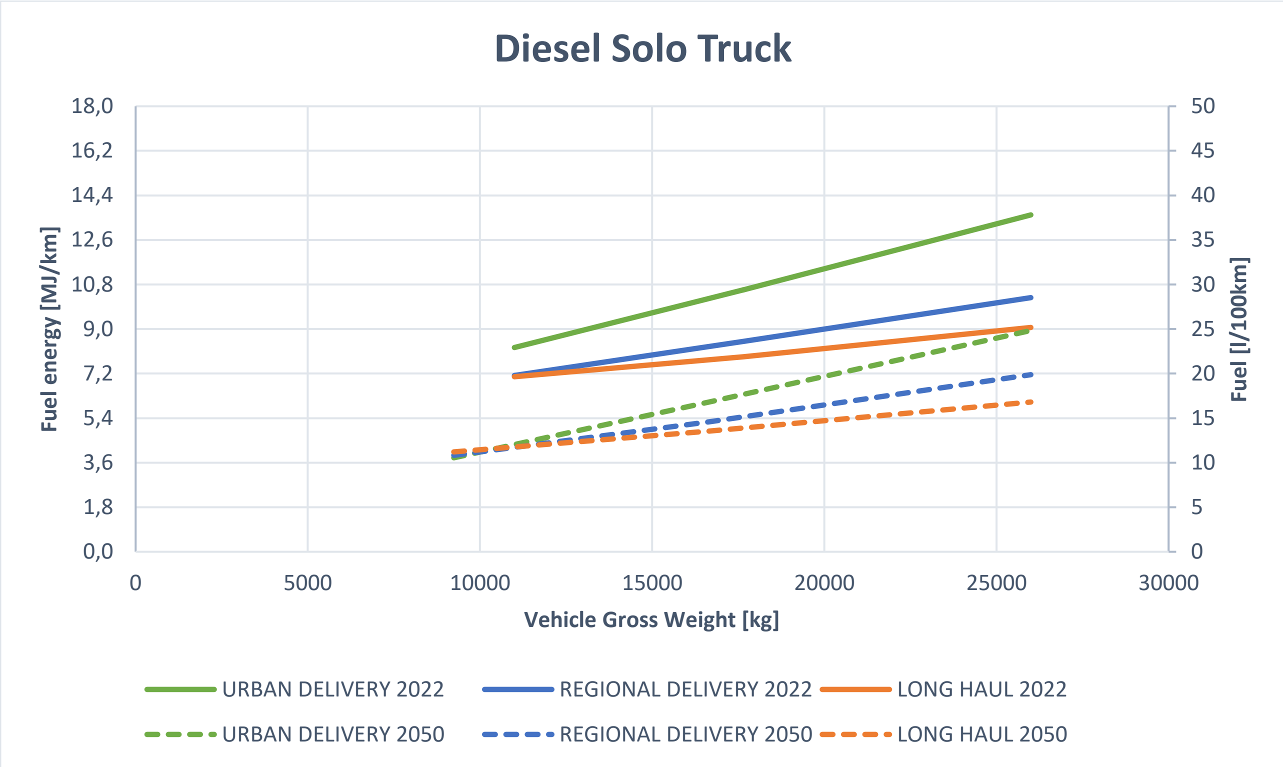

Figure 4 Predicted fuel economy in MJ/km and l/100km for diesel solo trucks.

(Berger, 2020) reports a consumption figure of 27.1 l/100km dropping to 25.9 l/100km in 2030 for a diesel solo truck. (Oscar Delgado, 2017) reports 26.3 l/100km for a 19-ton rigid truck.

The most relevant applications for solo trucks in Denmark are short-distance distribution of goods and miscellaneous work e.g., construction or garbage hauling. Common brands in Denmark are Volvo, Scania, Mercedes, Iveco, MAN, and DAF.

2.2. Truck with Trailer max 56 tons

A solo truck can also be used with a trailer for extra capacity. This is what is referred to as a truck with trailer or a road train. It can be configured for cargo or bulk transport, with a flat bed, a tilting tray, or a crane. Maximum vehicle weight with 7 axles according to legislation is 56 tons, and the expected development is that this will be raised in the future.

Figure 5 A picture of a representative vehicle (Spøttrup Kran- & Containerservice, 2023)

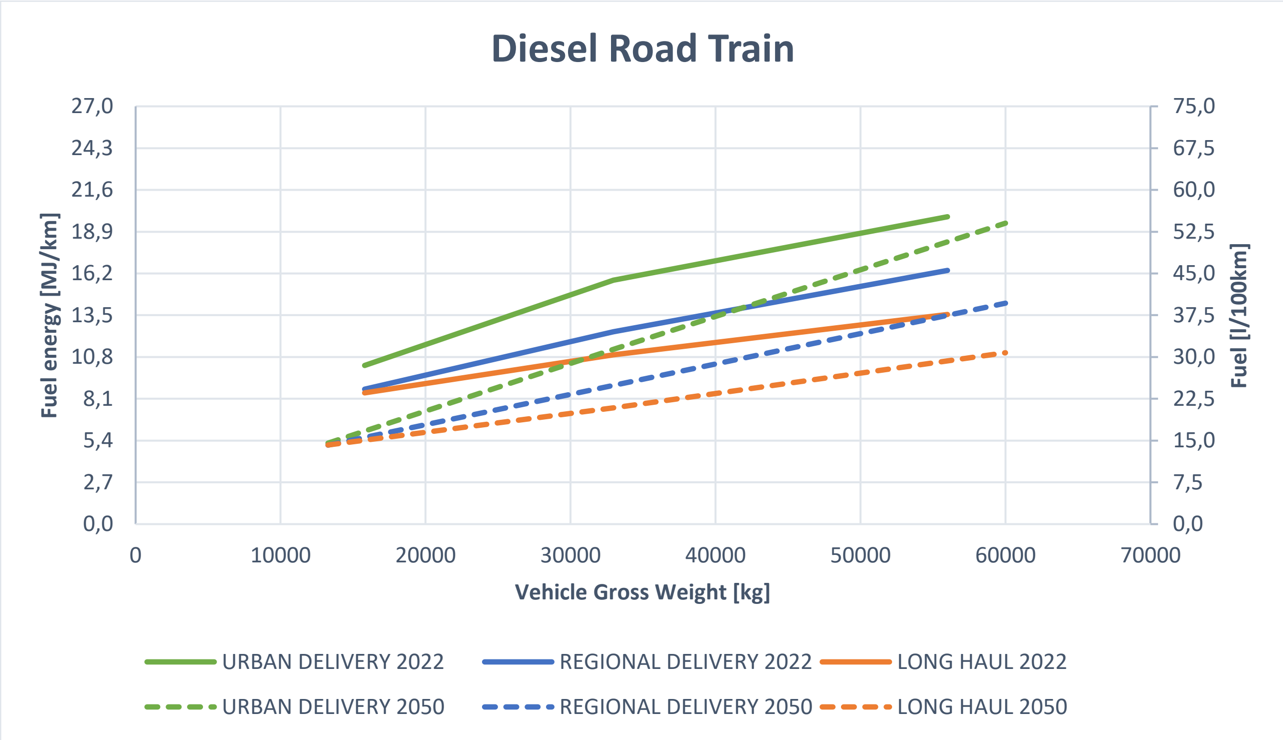

Figure 6 Predicted fuel and energy consumption for diesel trucks with trailer. Please note that the simulated 2022 diesel engine cannot produce enough power for the urban delivery cycle with a full payload at the speeds requested by the driving cycle. This causes the green solid line to break because the simulation software allows the cycle to be completed at a lower speed when the engine is underpowered.

The most relevant applications in Denmark are short-distance distribution of cargo and miscellaneous work e.g., construction.

2.3. Tractor-Trailer (Semi-trailer Truck) max 50 tons

A semi-trailer truck consists of a pulling vehicle, a tractor, which has a massive steel saddle that connects to a trailer. The difference between a semi- and a traditional trailer is that part of the weight of the semi-trailer rests on the tractor, while a normal trailer usually puts little or no weight on the tractor. It can be configured for container hauling, automobile transport, lumber, or bulk transport.

Figure 7 A picture of a representative vehicle (Spøttrup Kran- & Containerservice, 2023)

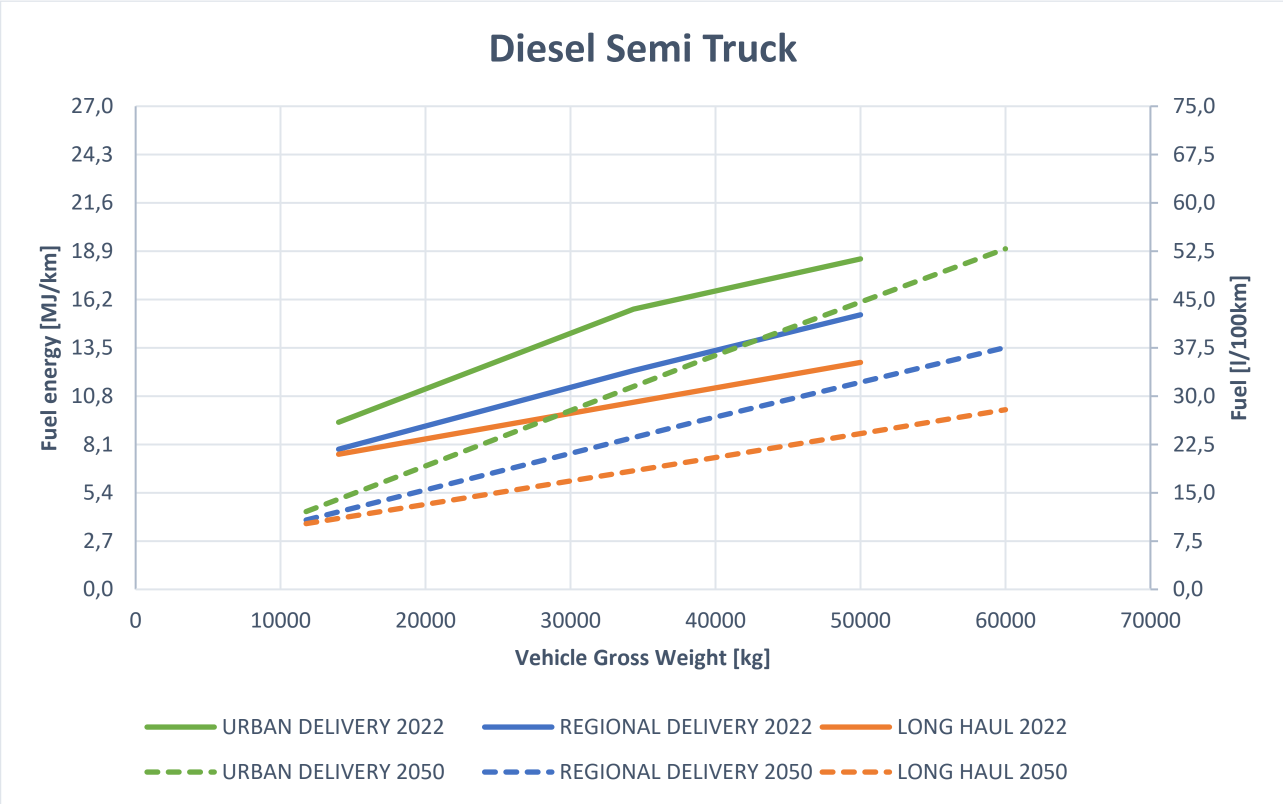

Figure 8 Predicted fuel and energy consumption for diesel semi-trailer trucks. Note that the simulated 2022 diesel engine cannot produce enough power for the urban delivery cycle with a full payload. This causes the green solid line to break because the simulation software allows the cycle to be completed at a lower speed when the engine is underpowered.

(Berger, 2020) assumes a consumption figure of 32 l/100km in 2023 and 30.5 l/100km in 2030 for a diesel semi. (Oscar Delgado, 2017) reports 36 l/100km for a fully loaded semi in long haul, 24 l/100km km/l for an empty one and 33.1 l/100km for a typically loaded semi. In urban delivery consumption goes up to 58 l/100km at full load. (Singh, 2014) reports 22 l/100 km for an optimized diesel semi-truck with a future goal of 19.3 l/100km.

The semi-trailer is suited for transporting refrigerated goods, cargo containers, liquids, or lumber. It is also frequently used for the transportation of other vehicles. Nowadays the trailers have been standardized so that any tractor can attach to any trailer. This adds flexibility because one truck can pick up different trailers at different locations. Some trailers are specifically designed to haul the standardized ISO-containers. Semi-trailers, even when refrigerated, can also be parked and function as temporary storage.

Semi-trailer trucks make up about one third of the total truck fleet in Denmark, but they drive more than two thirds of the total mileage (ref. Section 6). This makes semi-trailer trucks the most important segment in terms of energy consumption. The most relevant applications in Denmark are long-distance transportation of containerized cargo.

2.4. Route Traffic / Urban Transit Bus

An urban transit bus, also known as a city bus, is typically low-floor chassis with both seating and standing places. It is designed for easy access and passenger movements within the bus, rather than seating comfort. It is typically driven by a 6-cylinder diesel engine with automatic transmission. Gas and ethanol versions are also available.

Figure 9 City bus (Mercedes-Benz, 2023)

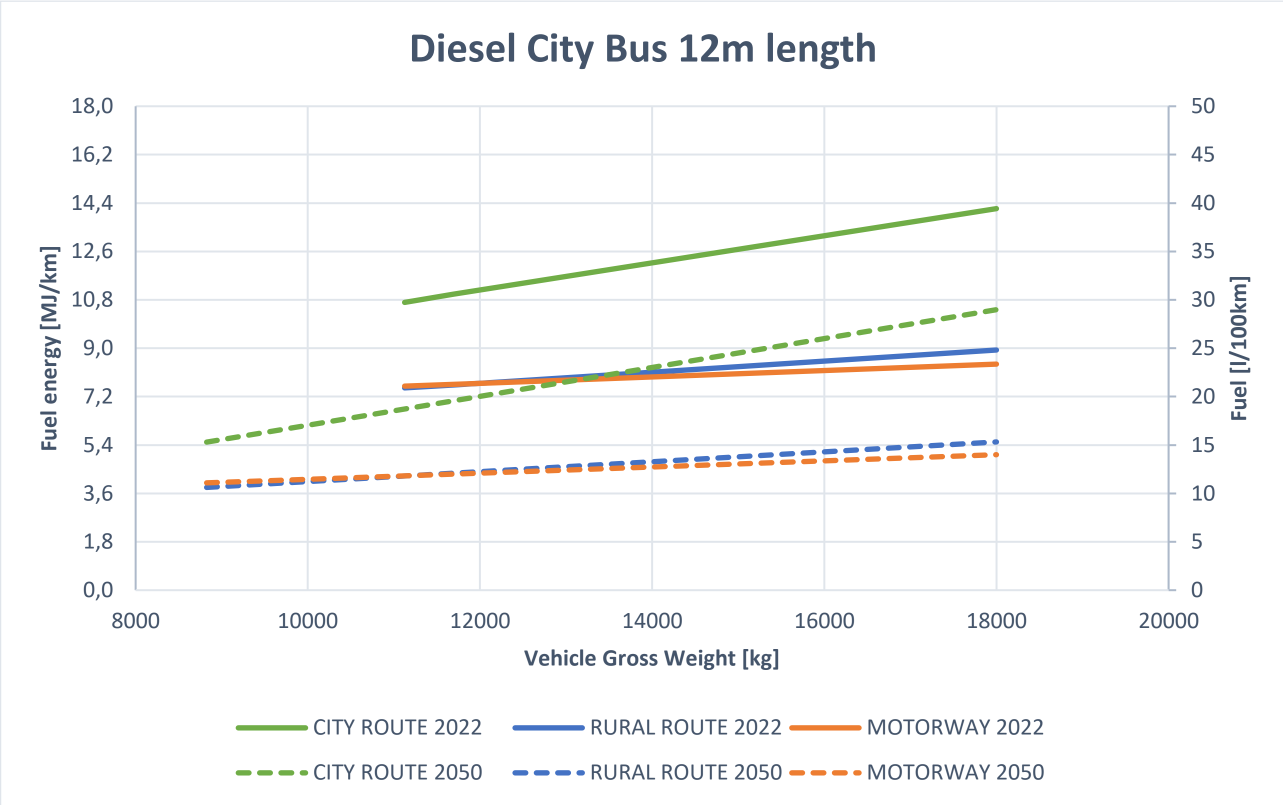

Figure 10 Predicted fuel and energy consumption of diesel city/transit buses.

According to MOVIA a 12 m diesel transit bus in the Copenhagen area uses about 35 l/100km. In smaller market towns consumption is reduced to 32 l/100km and in rural areas to 25 l/100km.

The current catalogue only includes buses above 12 meters with a minimum capacity of 50 passengers. Denmark has about 2.800 such ICE buses in operation on public routes. The number has been declining slightly due to the gradual introduction of electric buses. The product is very mature Cat. 4 with limited development potential.

Diesel buses are fueled in a traditional way at the garage compound on the bus company’s own premises. Some are fueled with biodiesel, but most are fueled with traditional B7. Some bus companies have successfully switched to buses with gas engines, and some have tried hybrids. The current bus market, however, is shifting more towards BEV buses. Ethanol buses are not used in Denmark.

2.5. Tourist Bus / Coach

A tourist bus, also known as a coach, is designed for longer trips at higher speeds, with room for luggage, a toilet and comfortable seating with installed seat belts. They are often double-deckers and can be arranged with sleeping cabins. The chassis is usually a high-floor chassis.

Figure 11 Diesel tourist buses/coaches (Mercedes-Benz, 2023)

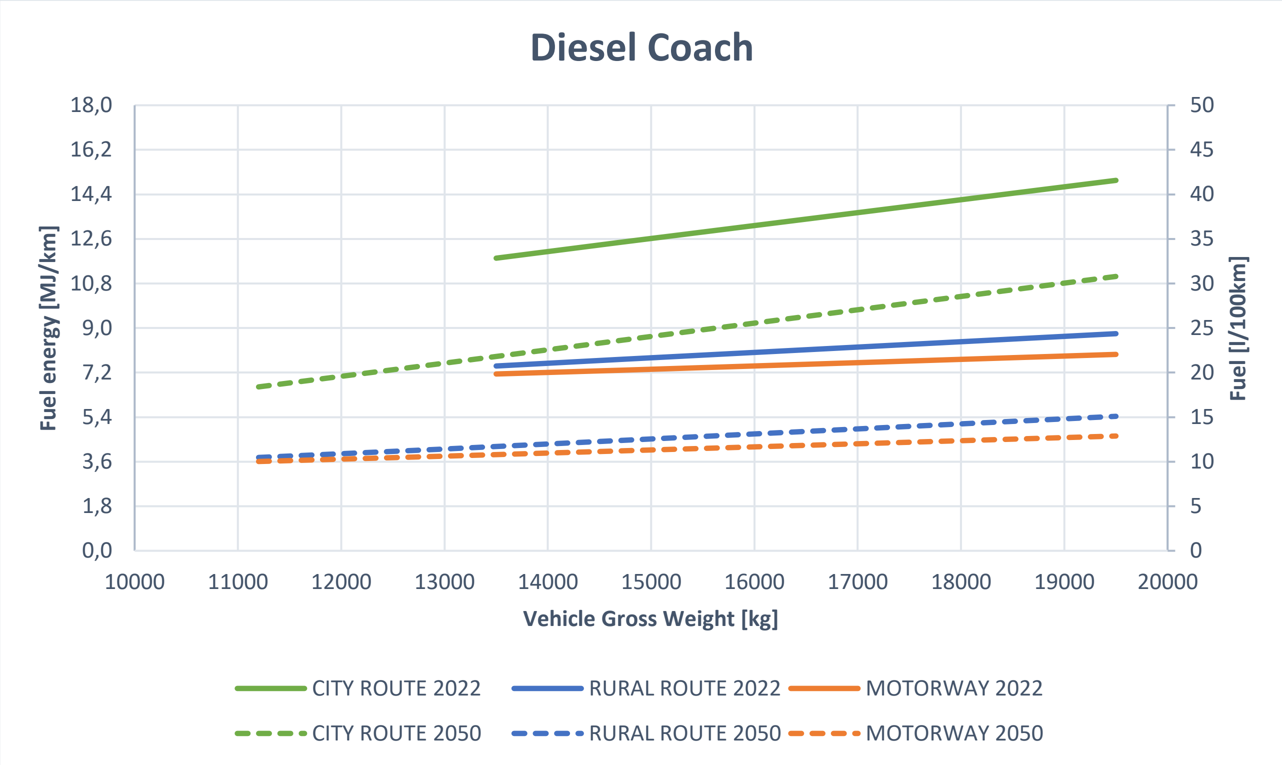

Figure 12 Predicted fuel and energy consumption of diesel coaches.

There are roughly 1.500 larger tourist buses in Denmark and many smaller buses which might be categorized as minibuses or minivans. The current catalogue considers only the larger versions above 12 tons.

They are typically equipped with a 6 or 8-cylinder diesel engine, designed to travel at up to 100 km/h on the motorway or climb mountain roads abroad. Gears can be manual or automatic. They may haul a small trailer for skiing equipment etc. A diesel coach can go door-to-door, practically anywhere, including ferry crossings. On routes up to 2000 km, they are a commonly used alternative to flying. On average, they carry twice as many passengers than urban transit buses (COWI 2015).

2.6. Datasheets

Datasheets can be found in the file 'Data_Sheets_for_Commercial_Freight_and_Passenger_Transport.xlsx'. This file (Dataark om tung vejtransport) is available on the Danish Energy Agency's website:
https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-tung-vejtransport

3. Qualitative description – Battery Electric Vehicles

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Description of powertrain technology

Electric heavy-duty vehicles on the market today are fundamentally based on the same chassis architecture as their diesel counterparts. The conversion from diesel to electric propulsion is achieved by replacing the diesel engine and gearbox with one or more electric motors and replacing the diesel fuel tanks with batteries as shown in Figure 13.

In some cases, the traditional rear axle and longitudinal drive shaft is replaced by an e-axle with integrated electric motors.

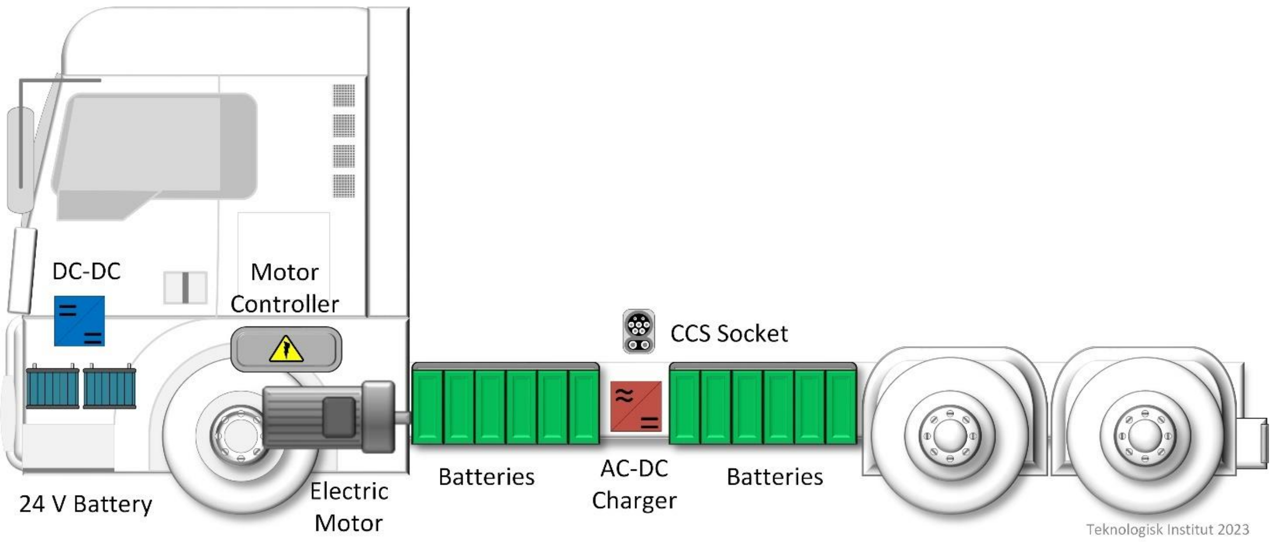

Figure 13 Classic layout of electric powertrain based on a legacy diesel chassis.

The essential components of the electric powertrain are:

- One or more electric motors. Many types of electric motors exist; induction type, synchronous type, permanent magnet ("DC") type, switched reluctance type etc. The motor types will not be explained in further detail.
- One or more externally chargeable battery packs. Most batteries today are the lithium-ion type, of which there are many variants, and future technology includes several other possible chemistries. Battery voltage is typically 400-800 V.
- An electric inverter system (motor controller) that transforms DC from the battery to a controlled AC-signal for the electric motor. This governs the speed and acceleration of the vehicle.

- A DC-DC converter that supplies 24V to the low-voltage battery and auxiliary systems such as lights, ventilation, and instrumentation.
- A charger that connects to an external source of electricity via e.g. a CCS socket, an AC-DC converter and/or DC-DC, for charging the high voltage batteries. Many types of chargers exist.

The technology is a Category 3 according to the Figure 1 (on technology maturity).

Electric heavy duty trucks on the European market have a median battery capacity of 240 kWh and a driving range of 240 km for payloads of 6 to 20 tons (Zeti, 2022). Currently available battery electric buses in Europe have a median range of 260 km for transit buses and 360 km for coaches. The selection of coaches is, however, limited (Zeti, 2022)

Available battery capacities range between 200 to 600 kWh, but as prices of batteries are dropping, we could soon see up to 1000 kWh or even more. As a rule of thumb, an electric bus or solo truck consumes about 1.0 - 1.5 kWh per km driven (see Figure 16, Figure 23). Thus, a future range of up to 1000 km is realistic.

Electric HDV's have a higher curb weight than the diesel counterpart, due to the weight of batteries. To compensate for this, Regulation (EU) 2015/719 and 2019/1242 allows a total of 2 additional tons of total weight for zero-emission lorries and three-axle articulated buses.

In the future, we might see even heavier electric vehicles. Electric trucks up to 74 tons have already been tested by Scania to demonstrate viability of heavy electric trucks.

The most prevalent use of electric heavy-duty vehicles in Denmark are public city buses (see section 3.4). These have already been successfully deployed in several Danish cities. The reason for this is, that city buses drive relatively slowly with many stops, and return to the same depot every night, where they can be recharged. Buses on fixed routes outside the city are also suitable for electric driving even though higher speed means shorter range. Tourist buses that travel non regular or more unpredictable routes are not in the primary scope because they often operate in areas without well-developed charging infrastructure (se section 3.5).

Many trucks operate on local routes with daily mileages below 500 km. For distribution in cities, solo trucks are most relevant (see section 3.1), but also bigger trailer trucks (section 3.2) and even long-hauling semi-trailer trucks (section 3.3) are candidates for electrification. We shall, however, note that driving with 56 tons requires up to 750 kW of motor power according to the simulations in this report. A truck with 400 kW of motor power will therefore loose speed in some of the cycles simulated.

Advantages/disadvantages

Electric motors attain high energy efficiencies. Because there is little or no idle loss, electric powertrains are especially efficient at low speeds and in start-stop operation. They are also suited for heavy loads because they require few or just a single gear ratio to accelerate and can regenerate braking energy.

One major drawback is the current limited driving range about 300-400 km between charges. The range diminishes with higher speed and load. As there are no common standards for the measurement and declaration of electric driving range of heavy vehicles, the advertised range shall not be understood as a guaranteed range. Depending on the driving conditions the actual range may be considerably longer or shorter.

Batteries are sensitive to extreme temperatures, due to two factors 1) battery cooling for optimal operation temperature and 2) climate control inside the driver cabin. Optimum driving conditions are around 21°C and colder weather will impact both charging speed and induce a higher power consumption for heating both the battery and the driver cabin. Climate control furthermore requires energy and reduces range.

High investment costs for electric trucks are currently major barriers for commercial application (Söderena, 2021). The current price difference for an electric truck compared to a diesel version is about 215 000 EURO (Scania, 2022). Total ownership is about 0.4 EURO/km higher. However, all-inclusive cost parity with diesel vehicles is expected by 2030 (Scania, 2022). This, however, depends a lot on the vehicle size and annual mileage. It will also be affected by economic incentives and regulations such as the coming Danish road-tax that will be differentiated among power trains.

As electricity replaces conventional diesel as a fuel there are some added considerations and possibilities. The cost of electricity varies greatly through the day and over the year in Denmark. This means that vehicle charging costs will decrease when the expensive peak-hours are avoided but also that charging during peak-hours will add costs for the operation. Charging outside peak hours might be obtained through careful charging planning or mitigated through a fixed-price agreement for electricity. It also implies that the necessary network of chargers is adequate in terms of geographic distribution and charging capacity.

The main battery is an expensive part of the vehicle and, with several daily recharging cycles it may reach its maximum number of cycles before the vehicle is to be scrapped. This means that a complete battery replacement could be needed within the lifetime of the vehicle.

Fueling or charging system

A typical charging system has an AC and a DC option with maximum AC power of 43 kW and maximum DC power of 375 kW. Charging takes about 1½ hours with the DC option and 9½ hours with the AC option, depending on the onboard charger of the vehicle. The prices of some common charging systems are shown in Figure 14.

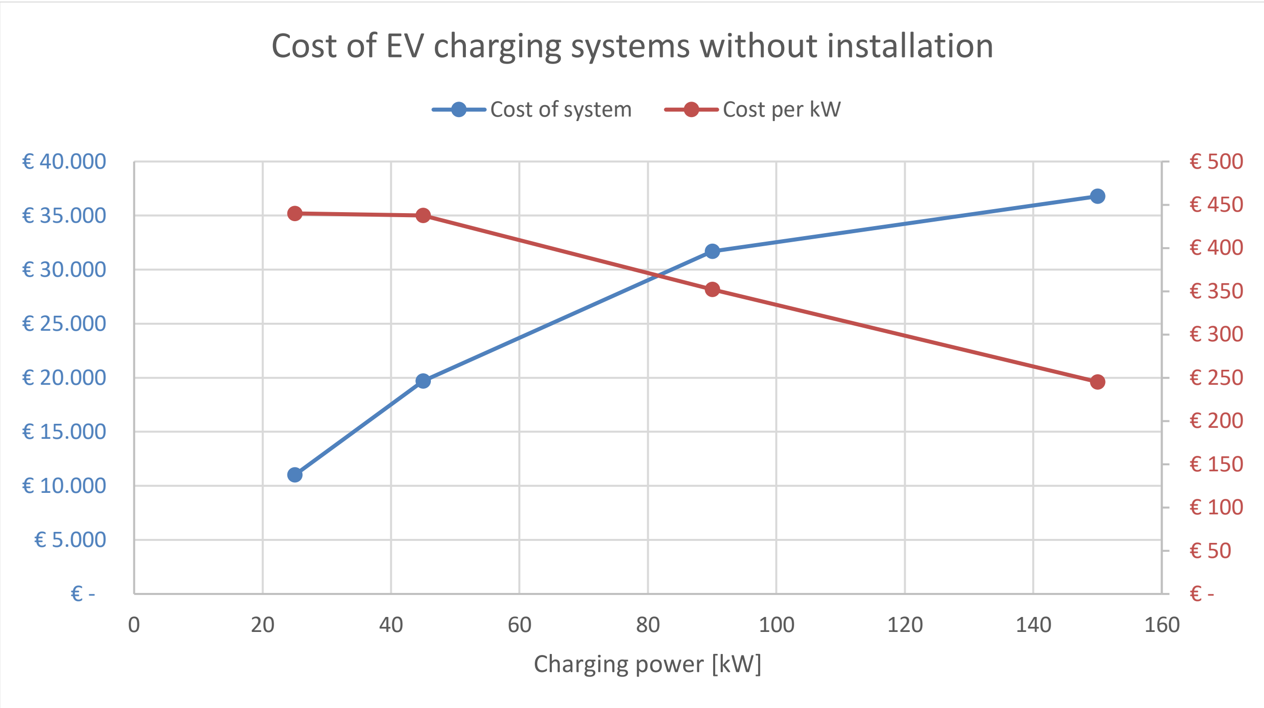

Figure 14 Cost of available charging systems without installation (Scania, 2021)

Notice that prices are without installation and that the grid connections for higher voltage charges can be costly.

Tesla has developed a significantly more powerful 1.5 MW charging system, which should add more than 600 km of range to a Tesla Semi in 30 minutes.

Electric buses can be configured for overhead charging such that batteries can be topped up at each bus stop. For trucks it is possible to establish e-highways, where charging is done while driving. Inductive charging through coils in the road is also possible but not a prevalent technology.

The future Megawatt Charging System MCS is briefly discussed in section 5.2.

Interaction with the energy system

Due to the technical charging requirements and electricity consumption of BEV trucks they must be integrated with the existing power grid. How BEVs interact with the energy system varies in relation to how and when they are charged. Battery electric vehicles may be charged either during trips along the highways on fast chargers or at a destination depot. Depending on the charging characteristics and behavior the electric HDVs may offer an efficient use of renewable energy from wind turbines and solar PVs. But charging may also increase the strain of the grid, inducing a need for grid reinforcements or even challenging the power adequacy. When connected to a charger, the vehicles have the potential to act in a vehicle-to-grid system providing different types of balancing or ancillary services. As markets for these different services to the grid and energy system are developed this can be a potential source of income for the vehicle owner or act as a cost-reducing component. The potential for flexibility and either negative or positive effects on the energy system depend completely on the driving patterns and application of electric HDVs.

Current market and technological status and future development perspectives

Electric city buses are present on the market and in use in several cities in Denmark. Electric trucks are not as common yet, however several large orders for electric trucks have been placed by Danish companies Mærsk, ARC etc. Manufacturers expect that 50% of new truck sales will be electrified by 2030 (Scania, 2021).

There are more than 30 000 electric heavy-duty trucks on the roads globally, the vast majority in China. Most of these are battery electric trucks, and most are Medium Freight Trucks. BYD, Cummins, Daimler, Emoss, and Fuso were first movers on the market. The Tesla Semi, perhaps the most well-known BEV Heavy Duty Truck model, has just recently entered in limited applications the market (IEA, ETP Clean Energy Technology Guide – Analysis, 2022).

In Europe there is 27 Medium truck models available, 36 Heavy models and 5 “others”. Total sales of electric trucks in Europe in 2020 was about 450 and electric buses were 2100 (IEA, Trends and developments in electric vehicle markets – Global EV Outlook 2021 – Analysis - IEA).)

The technological development of heavy electric vehicles takes place in the wake of electric passenger car development. The past 10 years have shown significant progress in performance and reliability of electric passenger cars. In the first Danish EV trials beginning in 2008 the cars were described as early prototypes with many system faults combined with a poor electric and mechanical reliability (Nørregaard, 2013).

In 2013-2015 a selection of factory built EV’s including the Tesla Model S and BMW i3 was tested in Denmark. The conclusion of this test was that the vehicles and component evolution was at a high state and overall performance could be rated as good (Benders, 2014).

As of 2022 there is a large selection of high performing passenger EV’s available. Towing capacity has been lagging behind ICE’s, but the latest BEV models are getting closer to be on par with ICE cars.

The rapid development of passenger size EV’s is expected to reflect on the heavy-duty segment as well. In the future, vehicle designers will be able to benefit from electric in-wheel motors which allow for a more flexible chassis architecture on trucks and buses.

Environment and climate

Electric motors are relatively silent and free of direct emissions to the air. They do not require frequent oil changes like ICE’s. Gearbox oil and battery coolants do need changing, but not as frequently. AdBlue is not needed at all since there is no exhaust system.

Danish grid electricity has a low carbon footprint, currently about 130 g/kWh and dropping to zero by 2030 (Energinet, 2021) so the base case for electric vehicles is good.

The largest factor is the battery production and end-of-life, which will add about 30 tons of CO_2 per vehicle. The CO_2 footprint of production is therefore about twice as high as an ICE truck (see section 5.4).

As battery recovery facilities are still limited, it is difficult to determine the end-of-life impact of BEV batteries. How batteries are reused or recycled is significant in relation to the sustainability of the technology.

Prediction of performance and costs

Prices of batteries are foreseen to drop significantly. It shall be noted that HDV battery packs are about twice the cost of passenger cars battery packs per kWh due to lower production volumes. This price difference is expected to even out by 2035 (ITF, 2022).

The current cost of HDV battery packs is about 250 EURO/kWh and this is expected to drop to about 60 EURO/kWh by 2050. Note that there is a markup on HDV battery price with respect to Electric passenger car batteries (ITF, 2022).

Predicted Total Cost of Ownership of electric trucks [€/km] compared to diesel trucks shows that lower-cost trucks are first to achieve cost parity (Müller, 2022)

Predicted cost of high-power charging systems are foreseen to drop significantly towards 2030 (Müller, 2022).

The electric motors for a BEV HDV typically produce 300-500 kW peak power. If the development matches passenger vehicles the future could bring much more power. This will allow heavy vehicles to better keep up with traffic, make overtaking safer and enhance the driving experience.

Uncertainty

There is some uncertainty as to the future weight, cost, and capacity of batteries. The general expectations on these parameters are, however, positive in terms of technical improvement, which is reflected in the quantitative sections of this report.

Cost and performance uncertainties are thoroughly investigated by (ITF, 2022).

It shall be noted that battery capacity is sometimes declared as gross capacity of the battery pack under test conditions and sometimes as net capacity restricted by the vehicle (useable capacity) which is about 25% less. The consumption figures in this report do not include losses during charging, which also depend a lot on the charging method.

3.1. Electric Solo Truck

An electric solo truck can be either 2- or 3-axle for gross weights up to 28 tons, which is two tons more than the legal limit for ICE trucks. This higher limit has been allowed in the EU to compensate for the extra weight of zero-emission powertrains. Electric trucks are usually configured for general cargo, but refrigerated options are also available. It is also suitable for duty as a garbage truck (refuse truck). Battery size for this size of truck is typically 300-400 kWh.

Figure 15 Electric solo truck (Volvo Danmark, 2023)

Common electric solo truck models on the EU market are (according to manufacturers' web sites):

- MAN eTGM
- DAF CF/LF Electric
- Mercedes eActros
- Scania URBAN BEV 1.0
- Volvo FE / FL Electric

The reasons for using EV's as refuse trucks are that their daily collection routes are quite short, rarely more than 100 km and average speed is also low. Since garbage is often collected early in the morning, a low noise level is also desirable.

Electric solo trucks are also suited for city distribution.

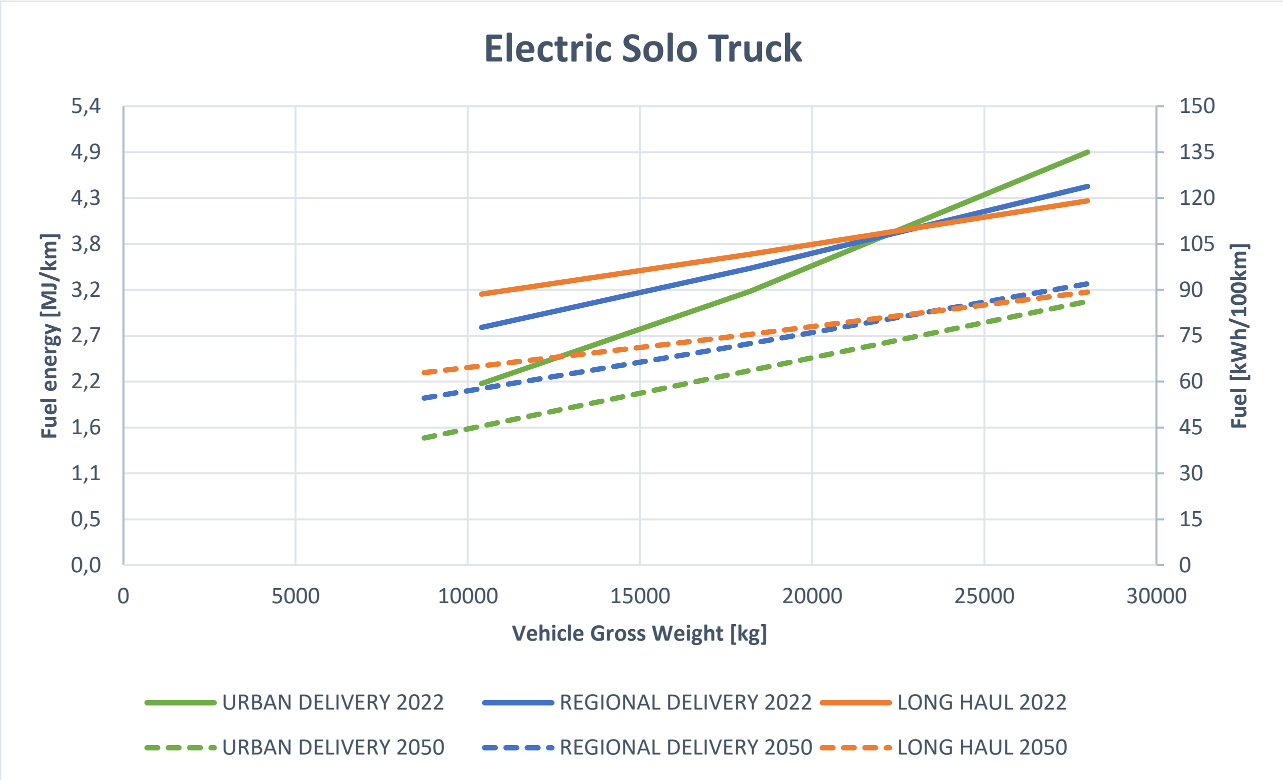

Figure 16 Predicted energy consumption for battery electric solo trucks.

(Berger, 2020) report a consumption figure of 110 kWh/100 km dropping to 105 kWh/100km in 2030 for an 18-ton rigid electric solo truck.

Electric trucks in the <28 ton size category were tested by (Müller, 2022). One of the interesting findings in that project was that urban driving was not always more economical than highway driving. This is also seen in our simulations in Figure 16, but only when the truck is fully loaded. We assume that limitations on the regenerative braking is responsible for this.

(Müller, 2022) investigated five major use cases for electric solo trucks.

- Retail store deliveries
- Consignee freight delivery
- Factory-to-warehouse delivery shuttle
- Beverage delivery from small brewery
- Factory-to-factory delivery

In a Danish context, similar applications also make sense. For instance, distribution of building materials from hardware stores has been implemented by Stark (Stark, 2021). The 28-ton electric solo truck has a 20 ton-meter electric-hydraulic crane mounted to it.

Distribution of milk is another case where electric solo trucks are being used in Denmark (Arla, 2020). An electric solo truck with refrigeration has also been purchased by Coop and will be used for city distribution in Copenhagen (Nielsen J. B., 2022).

3.2. Electric Truck with trailer

The combination of an electric truck and a trailer is not common in Denmark. The weight of such combinations can be up to 58 tons which, according to Danish Technological Institutes simulations, requires at least 600 kW of motor power to follow the standardized speed profiles used in this technology catalogue. Currently the biggest electric trucks are rated with a power of 490 kW. It is, however, not a technical problem to attach a trailer to an electric truck as shown in Figure 17.

Figure 17 Electric truck with trailer, gross total weight 40 tons (Mercedes-Benz, 2023)

Common models of electric truck that are suited for trailer haulage are:

- Scania 45 R/S Rigid 6x2*4 (64 tons, 450 kW)
- Mercedes eActros 300 6x2 (40 tons, 400 kW)
- Volvo FM / FH Electric Long Chassis (44 tons, 490 kW)

Figure 18 Predicted energy consumption of electric trucks with trailer.

Compared to the rigid solo truck (section 3.1), the range with a trailer is about 30% shorter (Mercedes-Benz, 2022). Even so, it is possible to get over 500 km of range with 40 tons and a 900-kWh battery, which is available today (from Tesla). To demonstrate the capabilities of electric road trains, an 80-ton electric truck is running on private roads in Swedish forests. This means, that electric road trains based on the European Modular System (EMS) up to 64 tons weight are technically within reach. Going from 40 to 64 tons will reduce the range by approximately 29% (Scania, 2021).

3.3. Electric Tractor-Trailer (Semi Truck)

In 2017, Tesla was the first company to announce electric semi-trucks for the US market. Deliveries of the Tesla Semi began in December 2022. Another American company, Nikola, followed with announcing the Nikola TRE BEV Europe Range, which is to be built in Germany, although the end goal of Nikola is a FCEV semi (see section 4.3). The Nikola TRE Europe Range will feature a 480 kW motor and 738 kWh battery. Range should be 500 km (Nielsen H. , 2022).

On the European market, electric semi-trailer trucks are still a relatively new technology. Scania has taken an order for 110 electric semi-trucks which are to be delivered during 2022 and 2023. Volvo also supplies electric semis. Danish shipping company DFDS has ordered 100 electric semi-trucks from Volvo. European electric semi-trailer tractors are mostly 2-axle, but 3-axle versions are now entering the market. The length of 3-axle electric semi-trailer tractors with room for sufficient battery packs are however challenged by the current maximum permissible vehicle length.

Figure 19 Electric semi-trailer truck, NIKOLA TRE (IVECO, 2023)

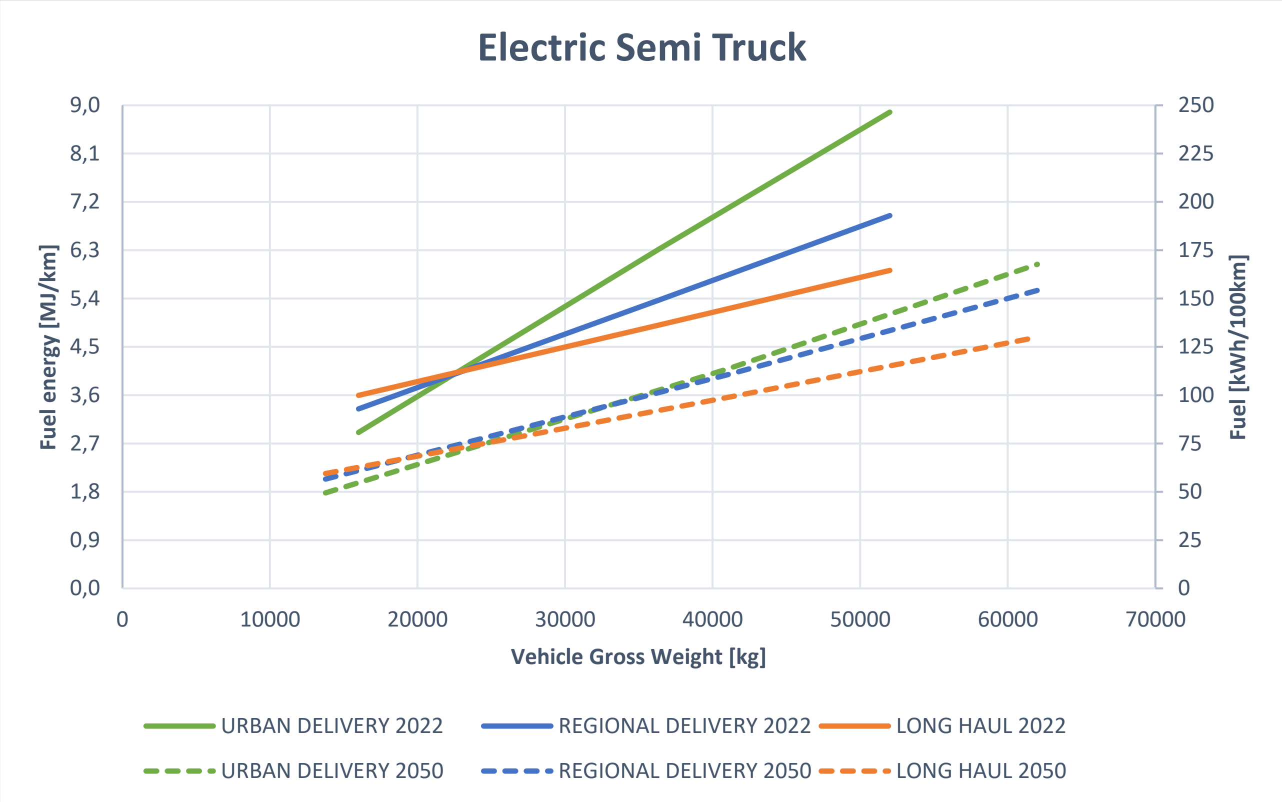

Figure 20 Predicted energy consumption of electric semi-trailer trucks.

(Berger, 2020) reports a mileage of 131 kWh/100km dropping to 127 kWh/100km in 2030 for an electric semi.

Current available models are e.g.:

- Scania Einride
- Volvo FM / FH Electric semi (44 tons, 490 kW)
- Volvo FE electric (27 tons, 225 kW)
- MAN E-TGM
- IVECO / Nikola TRE
- Tesla Semi (37 tons, 750 kW)

Electric semi-trucks are best suited to serve on pre-planned routes where charging infrastructure is in place. Given their relatively lower ranges, electric semi-trucks are, for the time being, unlikely to be used for long hauls. Instead, they're expected to be deployed on regional and urban routes, where the total distance traveled between destinations is much lower.

A 74 tons 3-axle electric Scania semi has been purchased by Swedish mining company Boliden. One modified Volvo (Futuricum Electric Semi 40E 6x2T) has a 900 kWh battery and travels a daily route of 500 km in Norway. One possible solution to the length and range problem is the use of e-trailers which are semi-trailers with built-in battery packs. It is currently being tested by the companies Trailer Dynamics, Krone Trailer and DB Schenker.

3.4. Electric Route Traffic / Urban Transit Bus

A battery electric bus resembles an ordinary bus (section 2.4) but uses an electric traction motor instead of the diesel engine. The traction batteries are placed on the roof or under the floor. Electric buses are very efficient due to the low average speed which is ideal for maximizing battery range. Furthermore, fixed routes allow optimum planning of charging spots. However, electric heat pumps or diesel heaters are needed for keeping the cabin warm in Nordic climates.

Figure 21 Electric city bus (Volvo Danmark, 2023)

There are about 600 000 electric buses on the roads globally, 95% of which are in China. BYD were first movers on the market and Yutong is now another popular Chinese brand.

In Europe there are 44 electric bus models available from over 14 brands. In 2021 more than 3000 electric city buses were sold in Europe which was a market share of 23%. In 2022 the market share has gone up to about 30% with an expected sales of 3600 electric buses over 8 tons (Chatrou, 2022). The total sales were 1768 in the first half of 2022 with VDL Bus, BYD, Yutong and Mercedes together accounting for half the sales. Other brands include Iveco, MAN, Solaris, Wrightbus, Volvo, Bluebus, Karsan, Ebusco, Von Hool (Chatrou, 2022).

Some common models in Denmark are:

- Ebusco 2.2 (Standard 12m, 13m, 13.5m and 18m, 250 kW)
- Ebusco 3.0 (Lightweight 12m and 18m, 250 kW)
- Yutong E12II (Standard 12m)

As of January 1st, 2022, there were 298 electric city buses above 8 tons registered In Denmark (Figure 22). By 2023 this number was 673. The rapid growth shows that electric city buses in Denmark is an overall success. It is therefore reasonable to expect a market share close to 100% within the next few years.

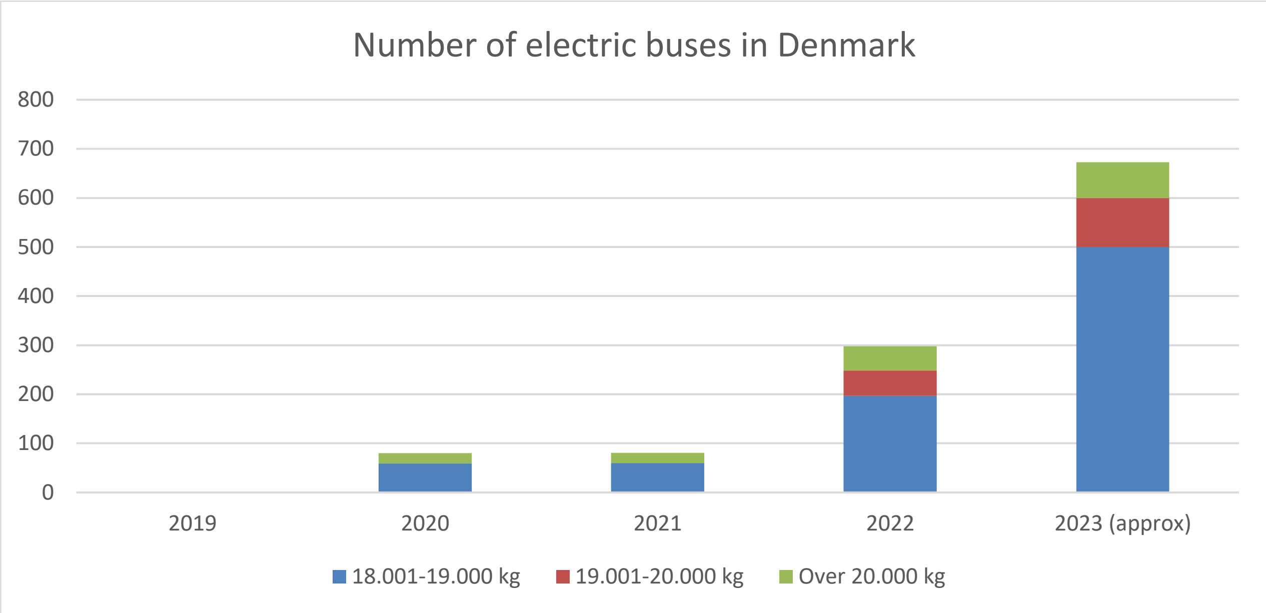

Figure 22 Development in the Danish inventory of electric city buses [# of buses] (Statistikbanken, 2022) has surpassed 600.

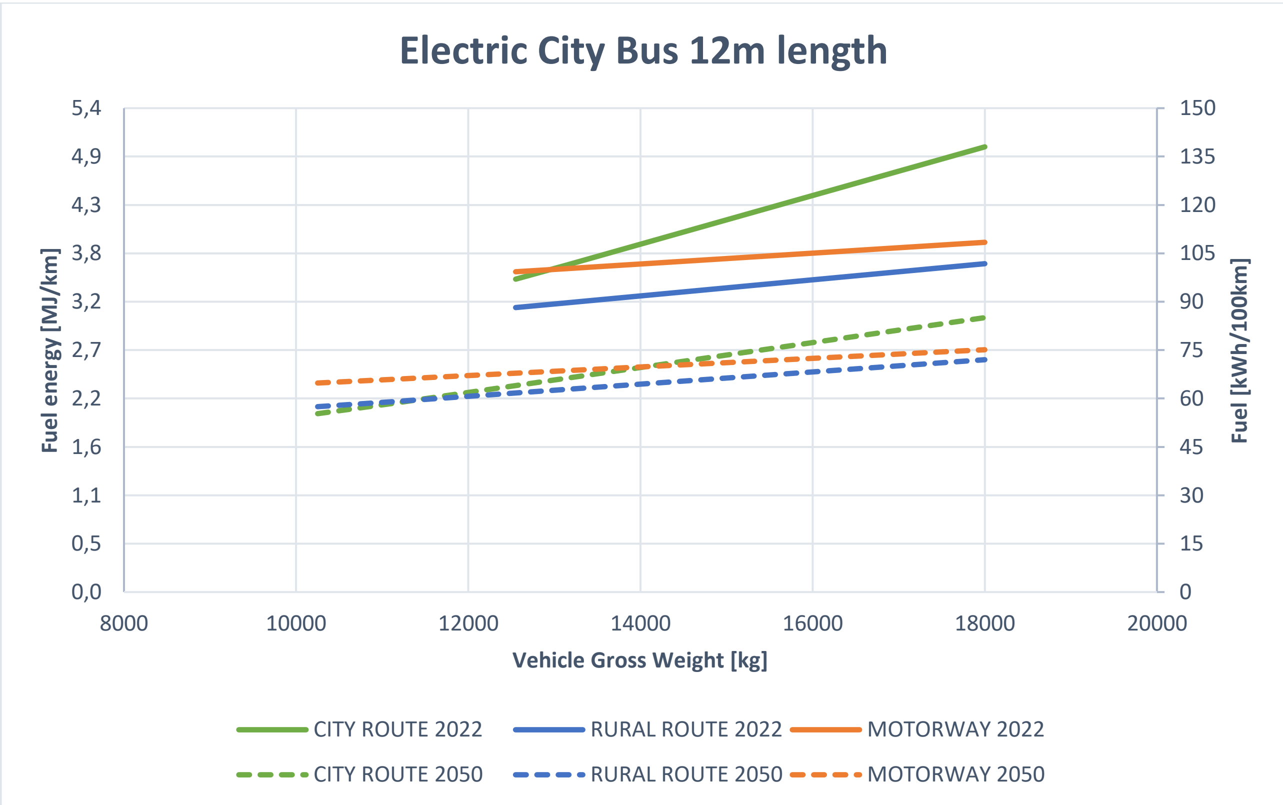

Figure 23 Predicted energy consumption of electric city buses

3.5. Electric Tourist Bus (Coach)

Electric tourist buses are less common than urban transit buses because they operate farther away from the bus depot and in many cases in areas where charging may not be available. Batteries are usually placed under the floor for better rigidity and stability compared to the low-floor models. Coaches will charge in the garage at night, but on longer trips they will rely on publicly available fast charging, which at the moment is still sparsely offered.

Figure 24 Danish Electric Coach (Andel Energi, 2023)

While it is technically possible to share charging facilities with passenger EV's, this is not practical due to physical obstacles and lack of parking space at public charging points. It may be necessary to install chargers for coaches at places where trucks don't usually go, such as amusement parks, tourist attractions, and hotels.

An example electric coach is Yutong T12E (350 kW, 422 kWh, 105 kWh/100km).

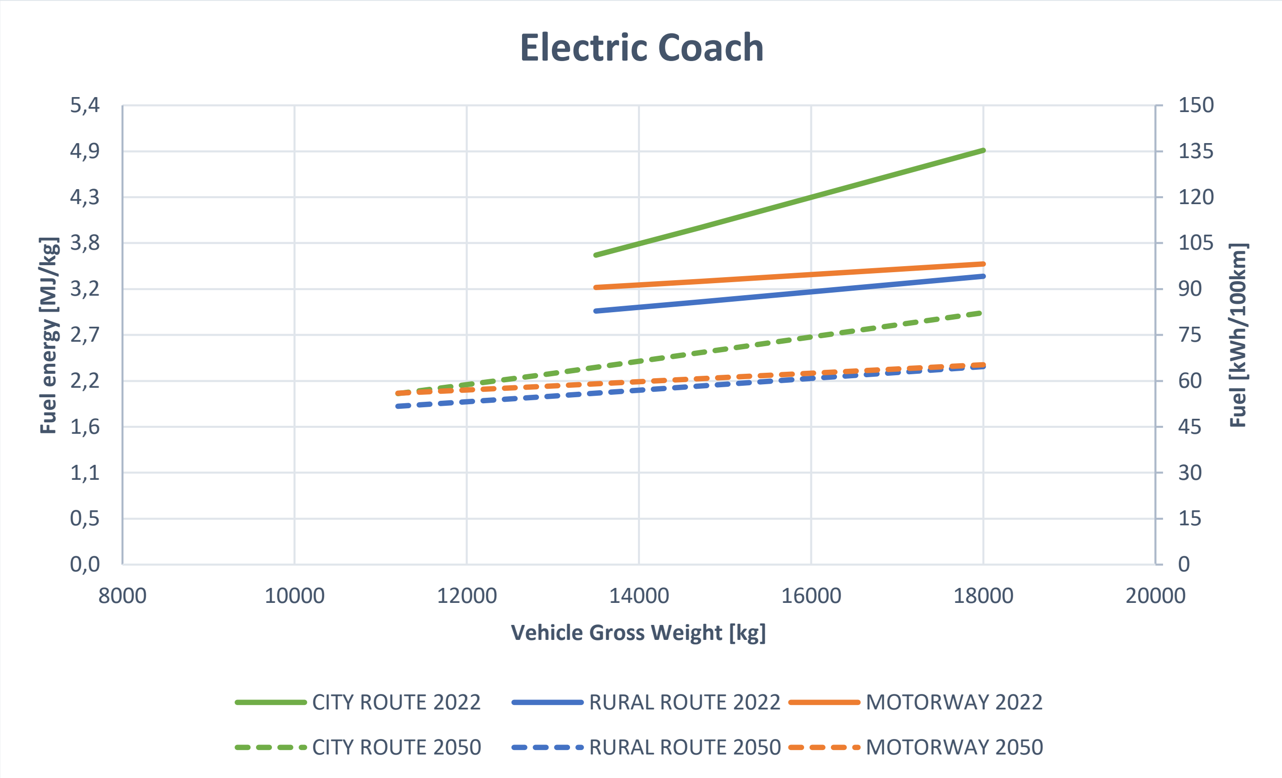

Figure 25 Predicted energy consumption of electric tourist buses.

3.6. Datasheets

Datasheets can be found in the file 'Data_Sheets_for_Commercial_Freight_and_Passenger_Transport.xlsx'. This file (Dataark om tung vejtransport) is available on the Danish Energy Agency's website: https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-tung-vejtransport

4. Qualitative description – Fuel Cell Vehicles

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- Reviewer: The Danish Energy Agency

Description of powertrain technology

A fuel cell vehicle (FCV) uses hydrogen as fuel. The fuel cell converts hydrogen to electric energy which is either stored in the battery or used momentarily by the electric motor. Similar to BEVs the electric motor in FCVs may also regain energy through regenerative braking.

The fuel cell is purposely not designed to produce the maximum power required by the vehicle but only the average power needed for operation of the vehicle. The rated power of the fuel cell is therefore lower than the rated power of the driveline as this capacity is provided from the combination of the battery and electric motor. The battery acts as a buffer to ensure that there is enough power for the vehicle to operate at full load when needed. The battery is not externally chargeable.

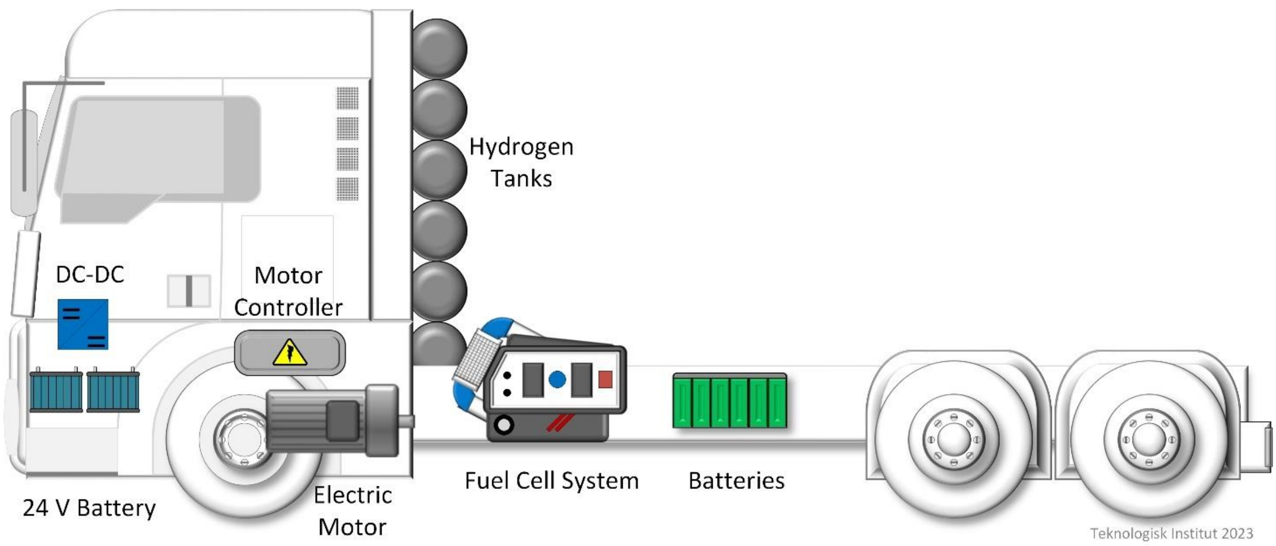

Figure 26 Fuel cell electric vehicle power train

Advantages/disadvantages

FCV have many of the advantages of BEV, such as low noise and vibration. Like BEV, FCV are also considered to be zero-emission in the tank-to-wheel perspective.

An advantage for FCV is the ability to be refueled with hydrogen in less time than it takes to BEV to recharge its battery. This enables a higher utilization of the vehicle.

The range of the FCV is only limited by the size of the hydrogen tank. This means that additional range can be achieved economically, by adding larger tanks. This makes FCV a promising technology in long haul operations.

A fuel cell configuration is typically lighter than an equivalent battery pack. Less powertrain weight translates to a higher payload or passenger capacity. However, the space needed for hydrogen tanks and cooling are also to be considered.

Since FCV are still not available in mass production, it is difficult to set a price or assess the cost of ownership accurately.

The energy efficiency of FCV is slightly higher than that of ICE vehicles but significantly lower than BEV due to the extra conversion step from hydrogen to electricity, which takes place in the fuel cell.

Hydrogen is yet an expensive fuel and the infrastructure for hydrogen refueling in EU is still very limited.

Fueling or charging system

The battery of a FCV is not externally chargeable. Hydrogen is supplied from a hydrogen fueling station with a standardized hydrogen refueling nozzle. The station can have on-site hydrogen production through electrolysis or use a swappable hydrogen storage tank that is replaced when empty (NEL, 2022).

The hydrogen tanks are filled with pressurized hydrogen at 350 bar. A typical fuel capacity is 32 kg. It takes between 8 and 20 minutes to fill the tank at a typical flow rate of 1-2 kg per minute.

Future systems are expected to hold 700 bar and up to 64 kg of hydrogen. Hydrogen can also be supplied in the liquid form (LH_2) at -253°C. This technology would increase the refueling rate to 8 kg per minute. Hydrogen storage data are provided by (ICCT, 2022)

In the case of liquid hydrogen there would be a boil-off problem to consider when the vehicle is not used.

The cost of hydrogen in Denmark is currently 14.5 EURO/kg, and as one kg of H_2 equals 33 kWh or 3.3 liters of diesel, hydrogen is currently the more expensive fuel per energy unit.

Interaction with the energy system

Hydrogen is one way of storing electric energy, which is useful in an energy system relying on fluctuating renewable energy sources. However, the physical distribution of hydrogen is currently a serious bottleneck. When and if sufficient hydrogen pipelines are built in Europe, it could be a game changer for hydrogen.. Hydrogen production by Power-to-X technology is currently being scaled up by e.g., Danish company Everfuel.

Current market and technological status and future development perspectives

FCV trucks are not yet produced for the mass market. Data for of currently available fuel cell trucks in Europe are available from (Zeti, 2022). The median driving range is currently 740 km. Median range of currently available FCV buses in Europe (Zeti, 2022) is 400 km.

The first-of-a-kind commercial FCV truck Hyundai XCIENT Fuel Cell has obtained 1600 orders for the Swiss market.

Daimler, Fuso, Toyota, Scania, Volkswagen, Volvo, and PSA are also developing FCV trucks, ranging from prototypes to commercial models. Scania has recently delivered some 15-ton FCEV trucks to Norway. Scania, Daimler, and California-based Nikola also have models at various stages between prototype and customer trials. FedEx and UPS are trialing fuel cell range-extender 12-ton delivery vehicles, and in Europe, the H2Share project is demonstrating several heavy trucks up to 27 ton (IEA, ETP Clean Energy Technology Guide – Analysis, 2022).

Environment and climate

Hydrogen itself does not produce CO_2 or any other carbon compounds when used as fuel in a vehicle. However, leakage of hydrogen molecules may have a strong but very short-lived climate effect itself, though the scientific research on this is still very limited. The actual climate impact of hydrogen vehicles depends heavily on the source and methods of hydrogen production. Upstream effects from sources and productions of fuels are not covered, as it is outside the scope of the catalogue, but these matters are covered extensively by e.g., Greet Fuel Cycle model (Lab, 2022). It should be noted however, that hydrogen comes from a variety of methods and sources ranging from “completely fossil” based to “completely renewable” based in terms of energy and production methods. If produced from extraction of fossil fuels, the impacts are significant. However, when based on renewable energy the impact can be low.

Prediction of performance and costs

Fuel cell cost is currently about 323 EURO/kW and expected to drop to 60-176 EURO/kW by 2050, according to cost and efficiency projections for fuel cell systems (ITF, 2022)

A comprehensive cost breakdown including cost of fuel cell systems etc. is also provided by (Berger, 2020).

See also (Transport & Environment, 2020).

Uncertainty

The cost predictions of fuel cells are quite uncertain. There is some consensus that manufacturing cost need to drop significantly, from 325 to 60 EUR/kW by 2050 (ITF, 2022).

The future cost of hydrogen is also very uncertain. Berger (2020) indicates a price span of 7-12 EURO/kg. In Denmark the price is currently around 13.5 EURO/kg.

Cost uncertainties are thoroughly investigated by ITF (ITF, 2022) who estimates a future price-range of 1.5-8.5 EURO/kg for hydrogen at the pump.

Additional remarks

A hydrogen combustion engine for trucks will be available in the near future at a significantly lower cost (Cummins, 2022). The new DAF XF H2 Innovation Truck with hydrogen internal combustion engine has won the European ‘Truck Innovation Award 2022’.

Other relevant EU projects are H2Accelerate, H2haul, Waterstofregio 2.0, REVIVE, and HECTOR.

4.1. Fuel Cell Solo Truck

The only FCV solo truck commercially available now is the 19 ton Hyundai Xcient Fuel Cell which has been deployed several places in Europe. The purchase price, however, has not been disclosed. The vehicles are mainly used by local logistics, distribution, and manufacturing companies.

Figure 27 Fuel cell solo truck (Hyundai Hydrogen Mobility, 2023)

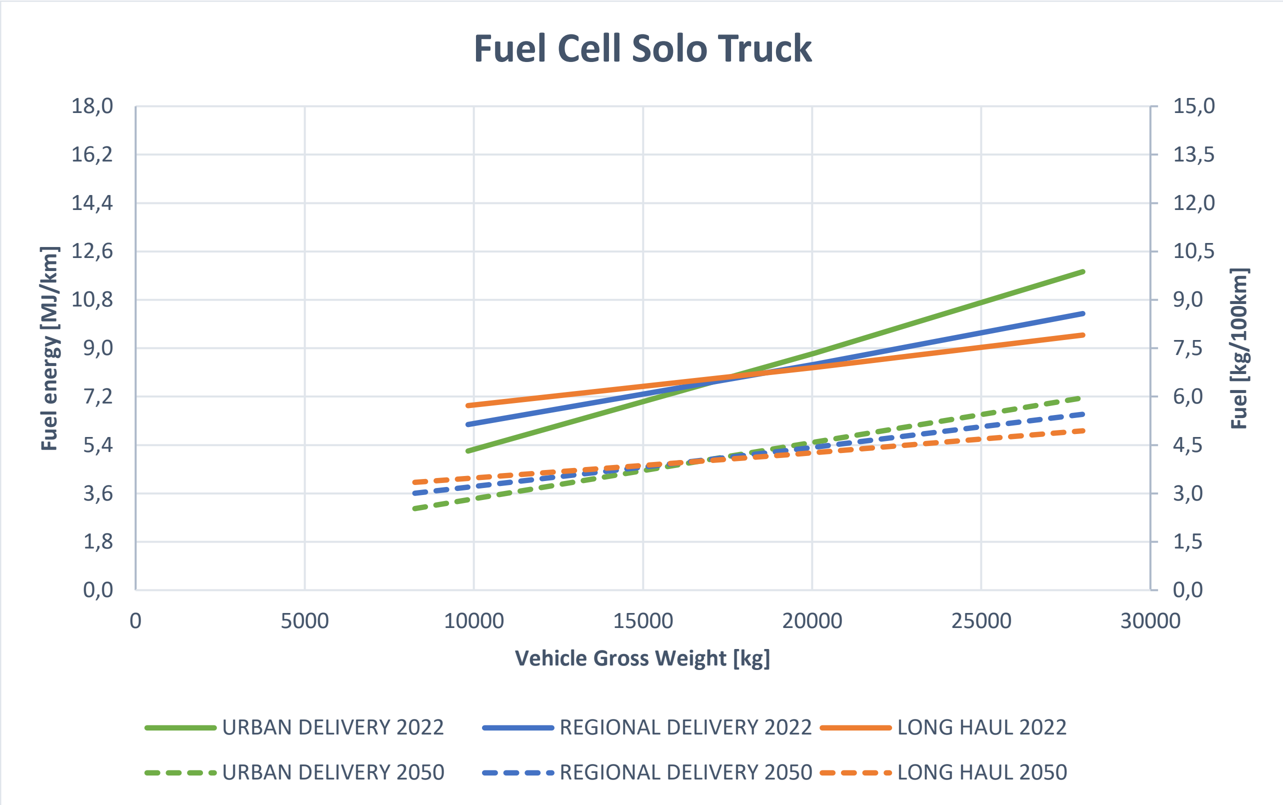

Figure 28 Predicted fuel and energy consumption of hydrogen solo trucks.

(Berger, 2020) reports a fuel economy of 7.10 kg/100km for a 27 ton rigid FCV truck with only marginal improvements up to 6.78 kg/100km foreseen until 2030. For a 19-ton truck like the XCient he reports 6.61 kg/100km now and 6.32 kg/100km in 2030.

The Xcient has 7 cylindrical hydrogen tanks placed behind the driver's cab. They hold 32 kg of compressed gaseous hydrogen at 350 bar. It also has a 72 kWh battery, acting only as a buffer (not externally rechargeable). It has two fuel cells delivering a total of 190 kW. The electric motor power is 350 kW. Driving range is not disclosed but from Figure 28 a typical range of 480 km can be estimated.

4.2. Fuel Cell Truck with Trailer

The aforementioned Hyundai XCient Fuel Cell (section 4.1) can weigh up to 36 tons with trailer. This combination is, however, not common.

Figure 29 Fuel Cell Truck with trailer (ESORO, 2023)

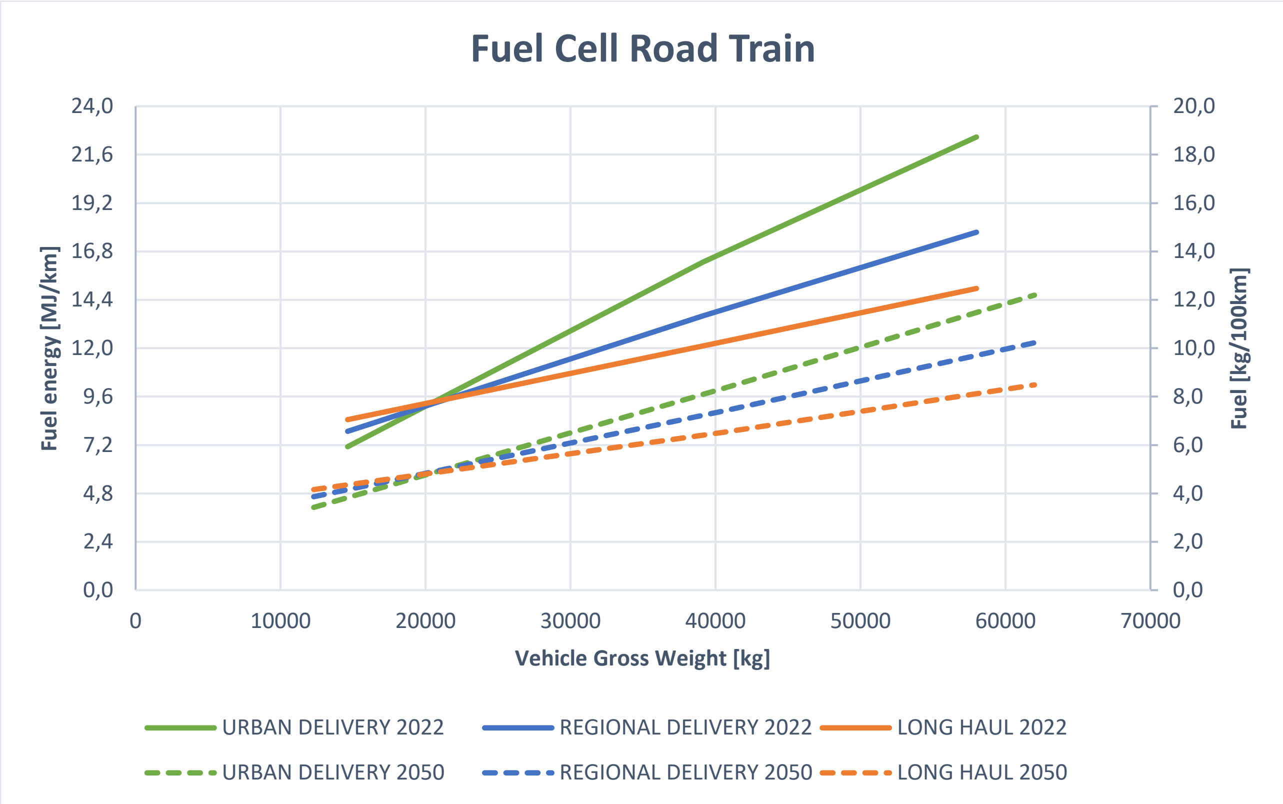

Figure 30 Predicted fuel and energy consumption of fuel cell trucks with trailer.

Fuel cells can in principle outperform batteries on longer journeys with higher average power demand. This means, that fuel cells could become the technology of choice for zero emission road trains with a high weight and long trips. The driving range with trailer and reefer according to Hyundai is 400 km, resulting in 8 kg/100km. Future hydrogen storage systems with 700 bar, in principle, enable twice the range.

4.3. Fuel Cell Tractor-Trailer (Semi Truck)

Fuel cells are an interesting alternative to batteries when requirements are longer range and shorter refueling times. This is often the case with semi-trailer trucks used for long haul operations. Fuel cell tractor-trailers, which are still in the development stage, were investigated thoroughly by ICCT (ICCT, 2022). The energy efficiency of hydrogen fuel cell semi-trucks is reported to be 10-12% higher relative to diesel but around 33% lower relative to battery electric vehicles (ICCT, 2022). The California-based truck start-up Nikola has managed to secure substantial funding and many pre-orders for its fuel cell semi-trucks. However, they have not yet been launched. It is important to note that US specification semi-trailer trucks may not be usable in the Danish transport system due to the maximum vehicle length.

Figure 31 Fuel cell semi- truck, Mercedes GenH2 (Mercedes-Benz, 2023)

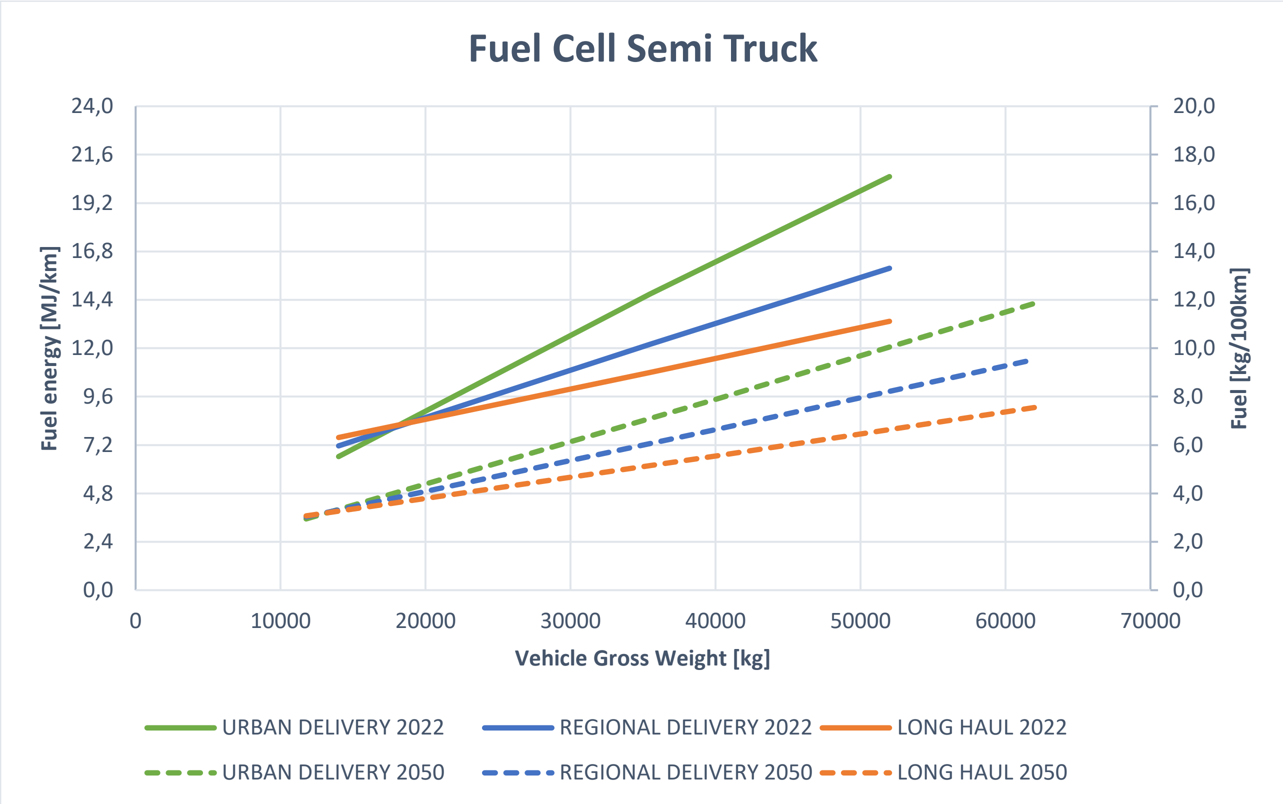

Figure 32 Predicted fuel and energy consumption of hydrogen semi-trailer trucks.

(Berger, 2020) estimates a fuel economy of 7.95 kg/100km for a FCV semi-trailer truck with only marginal improvements up to 7.58 kg/100km foreseen until 2030. ICCT (2022) reports an average of 9 kg/100km dropping potentially to 6.6 kg/100km by 2030.

4.4. Fuel Cell Urban Transit Bus

FCV city buses have been deployed in many European cities over the past 20 years, including Danish cities Copenhagen and Aalborg. Recently, however, the advances in battery electric buses (section 3.4), especially the declining cost of batteries are making it increasingly difficult for fuel cells to compete in this segment.

Figure 33 A Danish hydrogen fuel cell bus, Caetano (Toyota Danmark A/S)

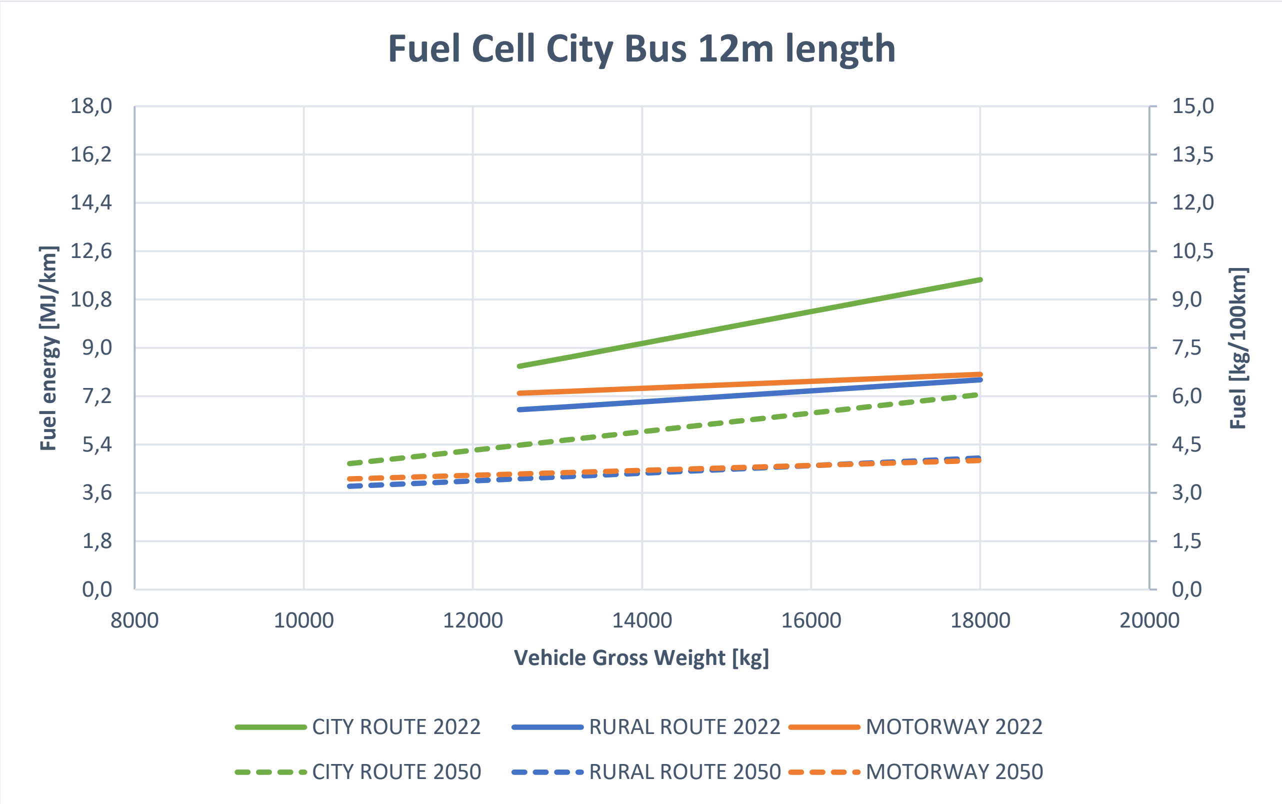

Figure 34 Predicted fuel and energy consumption of fuel cell hydrogen city buses.

Fuel cell buses have advantages in weight and range and therefore mainly compete with battery electric buses on daily routes above 500 km, where no intermittent charging or refueling is available. Hydrogen fuel cell buses are available as single deck 12 m, articulated 18 m bus and as double decker buses.

Reports of fuel economy vary greatly due to a large number of case studies from all over the world. Consensus is around 9-10 kg/100km with potential reduction to 8 kg/100km. One Dutch study reported a record-breaking consumption of 6.1 kg/100km for a Solbus. However, same study also reported a 30% increase of consumption due to electric heating in the wintertime. American/Canadian studies report up to 15.5 kg/100km.

China has most FCV buses in the world, with a fleet of around 5300.

Suppliers of FCV buses for Europe are Van Hool, Safra, Solaris, Toyota/CaetanoBus, ADL, Wrightbus, and Rampini.

The purchase cost of a 12 m fuel cell hydrogen bus is about 430,000 EURO (Hanhee Kim, 2021), which is expected to decrease to 360,000 EURO by 2030.

Variation in fuel cell bus consumption indicates a median of 8 kg/100km in summer and 11 kg/100km in winter with best result around 6 kg/100km (Data from RET Rotterdam 2018-2019).

4.5. Fuel Cell Tourist Bus (Coach)

Contrary to city buses, hydrogen coaches are still at the development stage and the cost is currently very high. European project 'CoacHyFied' (FEV, 2022) is engaged in comprehensive research and direct options for use of fuel cell powertrains for coaches. The lack of widespread fueling stations prevents them from entering the mass market at this time. Coaches run on both domestic and international trips with daily distances up to 1000 km.

Figure 35 Fuel Cell Coach (FEV, 2022)

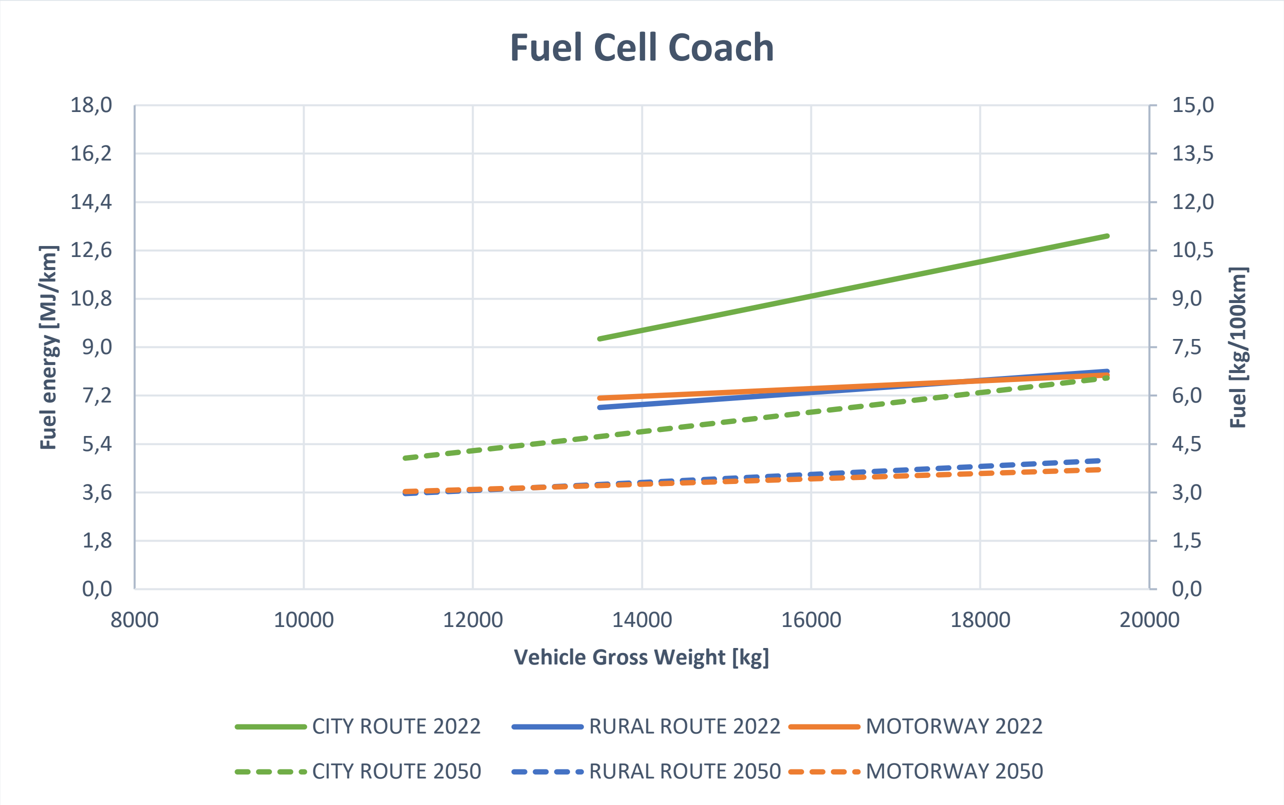

Figure 36 Predicted fuel economy of fuel cell coaches.

The efficiency of a fuel cell is best when the load is relatively low and constant. This can be achieved on longer journeys. Coachyfied aims at a consumption less than 10 kg/100km. Please note that the simulations in this report do not account for energy used for heating and ventilation of the bus.

Suppliers of hydrogen coaches are e.g. Otokar, Sinosynergi and Hyzon.

4.6. Datasheets

Datasheets can be found in the file 'Data_Sheets_for_Commercial_Freight_and_Passenger_Transport.xlsx'. This file (Dataark om tung vejtransport) is available on the Danish Energy Agency's website:
https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-tung-vejtransport

5. Quantitative description – All powertrains

The 15 vehicle specific tables related to this report are provided in a separate Excel-file named 'Data_Sheets_for_Commercial_Freight_and_Passenger_Transport.xlsx'.

All data refer to a new vehicle produced in the year indicated. All cost data are stated in fixed 2022 EURO prices excluding value added taxes (VAT) and other taxes.

The level of uncertainty is stated for the most critical figures such as investment cost and efficiencies. Other figures are considered when relevant.

Secondary data in the tables are referenced by a number in the utmost right column (Column N: 'Ref'), linking to source specifics explained in the 'References' sheet.

Notes in Column M: 'Note' can include additional information on how data was obtained.

5.1. Documentation of central assumptions behind the data tables

This section quantifies the central assumptions which form the basis for all vehicle simulations reported in the tables.

Modelling assumptions

The vehicle simulations were done using in-house modelling software at DTI which in the public version is known as "Grøn Beregner" – "Green Computer". The software was initially calibrated to match the results of the European Commission official tool 'VECTO' (Vehicle Energy Consumption calculation Tool - VECTO) and the simulation results from ICCT (Oscar Delgado, 2017). Figure 37 shows the appropriate correlation between the tools.

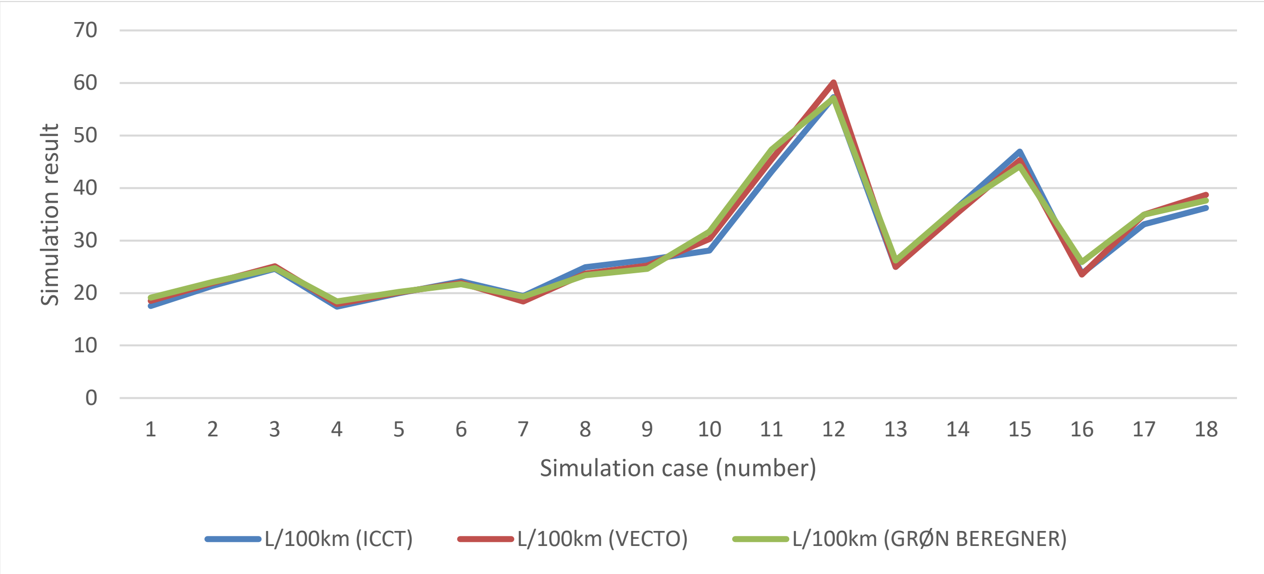

Figure 37 Correlation between VECTO, ICCT and in-house software (GRØN BEREGNER) – 18 simulations done

The simulations rely on fixed drive cycles as shown in Table 1.

Table 1 Drive cycles used for simulation.

Vehicles	NAME	Drive cycle	Average speed
Trucks	URBAN DELIVERY	VECTO Urban Delivery	30.7 km/h
	REGIONAL DELIVERY	FIGE	59.0 km/h
	LONG HAUL	FIGE_HIGHWAY	86.9 km/h
Buses	CITY ROUTE	Copenhagen Line 1A	26.9 km/h
	RURAL ROUTE	FIGE	59.0 km/h
	MOTORWAY	FIGE_HIGHWAY	86.9 km/h

The simulation tool uses rolling resistance and aerodynamic drag to calculate the mechanical energy on a second-by-second basis, then uses Newtons second law to determine inertia forces. From a series of charts and algorithms the energy balance is established as shown in Figure 38.

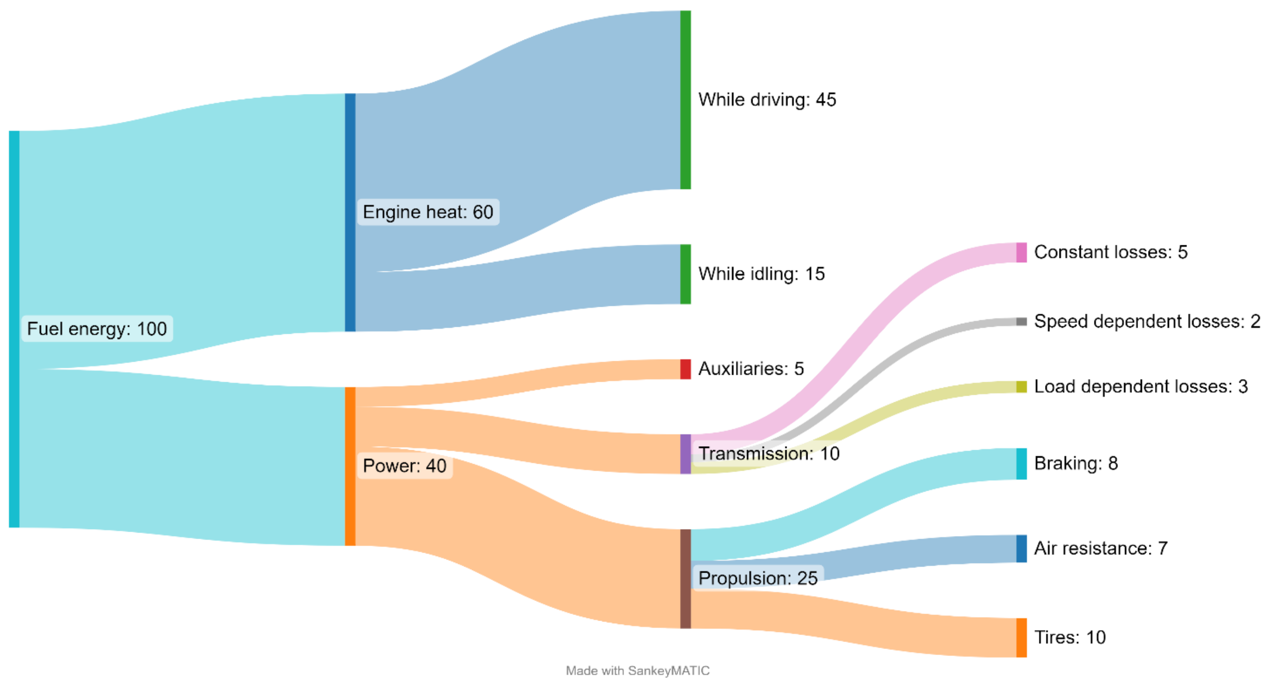

Figure 38 Basic energy balance for a vehicle as used in this report (this graphics is representative of diesel)

The simulation does not include:

- Technologies such as platooning will lower fuel consumption by 5 -15 % in the long-haul sector
- Use of energy for heating which can amount to 30% extra consumption on electric buses during cold winters

Rolling resistance

Due to the force of gravity, a vehicle tire deforms slightly upon contact with the road surface. The deformations cause a rolling resistance that opposes the rotation of the tire. Since 2012 all tires in EU have been labelled with a rolling resistance coefficient C_{RR}. The coefficient defines the ratio between the rolling resistance force and the normal force (generated by the vehicle mass) that acts on the tire. The engine power that is consumed by the rolling resistance increases linearly with the vehicle mass, vehicle speed and C_{RR}. Typical C_{RR}-coefficients for heavy-duty vehicle tires are today around 0.006. Class A tires with C_{RR}-coefficients of 0.004 are available, but they are not expected to be widely adopted until after 2030 (Oscar Delgado, 2017)

Table 2 Rolling resistance factors used for simulations.

	2022	2025	2030	2040	2050
Relative fR	100%	97%	94%	87%	80%
Absolute value fR	0.0050	0.0049	0.0047	0.0043	0.0040

Aerodynamic drag

Aerodynamic drag is generated by ambient air and acts as an opposing force on a moving vehicle. The drag increases by a factor of four every time the air speed is doubled. Aerodynamic design of a vehicle has therefore a significant influence on fuel consumption when the vehicle is driving on highways. Consequently, it is less important when the vehicle travels at lower speeds during urban deliveries. The ability to resist the drag is quantified by the vehicles drag coefficient C_D that varies with the vehicle category, as illustrated in Figure 39.

Vehicle type	Typical range of C_D values
Truck with trailer	0.55-0.85
Semi-trailer truck	0.47-0.75
Bus	0.40-0.65
Van	0.35-0.50
Passenger car	0.26-0.40

Figure 39 Typical drag coefficients of different vehicle categories - from literature

A rigid solo truck can achieve an aerodynamic drag reduction of 23 % relative to a baseline truck (Landman, 2011). In few years, the best configuration will have a C_D of around 0.45 (Oscar Delgado, 2017) as listed in Table 3.

On a Semi-trailer Truck the aerodynamic drag is influenced by the combined design of the tractor and the trailer. It can be reduced by adding fairings/skirts along the side and at the rear end (tail) of the trailer. Streamlining of the tractor nose, use of active grill shutter, aerodynamic mirrors (or rearview cameras), wheel covers, and integrated tractor trailer design can yield a C_D-coefficient of 0.35 as achieved in the US Super truck I program. The Freightliner Cascadia US class 8 truck is an example of a Super truck with optimized aerodynamic design. Moreover, some concept trucks in the European Union have achieved a C_D-coefficient of 0.3 (Kopp, 2012).

The truck with trailer vehicle category is less streamlined compared to a Semi-trailer Truck. Nevertheless, most of the drag is caused by the front surface (that faces the main flow direction) and at the wake that forms at the back end of the vehicle. Studies have also found that the C_D-coefficient of a Long trailer Truck (comparable to European Modular Concept), is around 0.55 which is only 10 – 22 % higher than that of the conventional truck (Martini, 2011).

For a highway coach the body is close to the ground and is effectively incorporating side skirts, and unlike a truck, it has no tractor-trailer gap. Aerodynamic drag is most efficiently reduced by rounding of the forward corners (sides and top) and by making a more tapered forebody. A recent bus design shown in Europe is characterized by a drag coefficient of 0.35 (Hamsten, 2002). With optimized configurations a C_D-coefficient as low as 0.28 is even reported in the literature (Patten, 2012).

Table 3 Aerodynamic coefficient of different vehicle categories – from literature and for simulation

Type	Litterature Baseline	Litterature Best configuration	Simulation 2022	Simulation 2050
Rigid truck	0.58	0.45	0.58	0.45
Semi-trailer truck	0.60	0.35 (Tesla Semi)	0.60	0.35
Trailer truck	0.70	0.55	0.70	0.55

Coach Bus	0.55	0.35	0.55	0.35
City Bus	0.65	0.40	0.65	0.45

Engine peak efficiency

Engine peak efficiency is defined as the power output at the crank divided by input fuel power in the most efficient operating point. The peak efficiency of diesel engines has improved over the years, and is currently around 40-45%, and is thereby still linked to a substantial energy loss though heat. It is foreseen that diesel engines could reach peak efficiencies of 60% in the future (Singh, 2014).

Table 4 Peak efficiencies collected from literature.

Powertrains	Data Source	2022	2030	2050
Diesel	(Oscar Delgado, 2017) (Singh, 2014)	42% ~50%	47% ~55%	- ~60%
Electric	Mean value obtained from simulations (VECTO, 2022)	78%	-	85%
Fuel cell	(Transport & Environment, 2020) (ITF, 2022)	54% 45-50%	56% 50-62%	- 55-66%

The peak efficiency for a rigid truck diesel engine is expected to improve by 5.1 % points in 2030 compared to present (baseline) of around 42.2 % (Oscar Delgado, 2017). The engine manufacturer Cummins has indicated that medium-duty engines can achieve an efficiency of around 47 % within the 2020–2030-time frame (Eckerle, 2015). Another manufacturer Achates Power plans to achieve 55 % BTE engines using optimized engine design (Abani, 2017). During the Supertruck 2 program (set by the US Department of Energy), Cummins has demonstrated a BTE of 55 % for a class 8 truck (NewsDirect, 2021) which has been achieved through engine component modifications end the use of waste heat recovery.

Table 5 Engine data used for simulations in this report.

	Diesel		Electric		Fuel cell electric	
Year	Peak power	Peak efficiency	Peak power	Peak efficiency (motor * inverter *battery)	Peak power	Peak efficiency (motor * inverter * fuel cell)
2022	380 kW	42.6%	290 kW	0.93*0.96*0.94=84%	290 kW	0.93*0.96*0.54=49%
2050	735 kW	49.0%	800 kW	0.94*0.96*0.98=88%	800 kW	0.94*0.96*0.58=51%

Electric and fuel cell efficiencies are a combination of motor-, inverter-, battery- and fuel cell efficiencies. In this table, the FCEV peak efficiency is calculated without potential battery loss as the fuel cell is expected to deliver the motor power when possible.

Mechanical losses

We are assuming mechanical loss factors to be identical across fuels and vehicle types and to be reduced gradually towards 2050 is shown in Table 6.

Table 6 Mechanical loss factors used for simulation.

	2022	2050
Relative	100%	60%
Absolute	5% + 50 N + 0,5 N/kmh	3% + 30 N + 0,3 N/kmh

5.2. Technical parameters

These parameters are also used in the accompanying data tables.

Maximum vehicle payload/number of passengers

Maximum payload in kg is calculated from:

MAXIMUM ALLOWABLE GROSS WEIGHT [kg] – VEHICLE MASS IN RUNNING ORDER [kg}

For buses the maximum payload is the number of passengers allowed.

The trend is that higher gross weight for trucks is being allowed, currently up to 60 tons is being trialed, which can translate to 50% more payload per truck with only 26% increase in fuel consumption (Table 7). It is evident how higher payload yields higher cargo energy efficiency. Larger trucks are inherently more efficient per ton-km of cargo than smaller trucks.

Table 7 Cargo efficiency by truck size –" the bigger the better"

Vehicle	Light VAN 50% load (TEMA)	Light TRUCK 44% load (TEMA)	Heavy truck 44% load (TEMA)	Heavy truck with trailer 14t cargo (NVF/Volvo)	Articulated truck with trailer 21 t cargo (NVF/Volvo)
MJ/ton-km	3.13	2.74	1.04	0.85	0.71

This represents a dilemma in the assessment because larger trucks will automatically win by comparison but are not suitable for every kind of transport job. The Excel file behind this technology catalogue[5] also contains a sheet with detailed simulation data, which shows the increased freight efficiencies in MJ/(ton*km).

Mass in running order

For all powertrain-segment combinations, the mass in running order means the mass of the vehicle with fuel tanks filled to at least 90 % of its or their capacities, including the mass of the driver, of the fuel and liquids, fitted with the standard equipment in accordance with the manufacturer's specifications and, when they are fitted, the mass of the bodywork, the cabin, the coupling and the spare wheel(s) as well as the tools.

The typical masses of trucks and trailers are taken from various manufacturers' websites, transport companies and partly from (Oscar Delgado, 2017), (Lab, 2022), (Lastas, 2022). The important issue is the expected effect of future light-

5 Available at https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger

weighting. Lightweight materials will lower the weight of the truck by up to 2300 kg (Oscar Delgado, 2017) in the long term.

Table 8 Assumed vehicle weight reductions due to lightweight materials - all vehicle segments

	2022	2025	2030	2040	2050
Relative weight	100%	98%	95%	90%	84%
Absolute reduction	0	-317 kg	-714 kg	-1507 kg	-2300 kg

Vehicle maximum gross weight

Maximum gross weight is a matter of legislation. The development is such that heavier vehicles will be allowed on the road in the future, beginning 2025 in Denmark with 11 initiatives (Danish Transport Ministry, 2022).

The allowable size of trucks is expected to increase because increased payload is crucial for the overall performance of the trucks. In general, extra weight on the vehicle cost very little extra fuel, so performance in terms of energy per ton-km increases unambiguously with size.

Maximum vehicle weight for semis according to EU legislation is 42 tons, and the expected development is that this will be raised in the future.

The maximum weight of road trains is more than 44 tons depending on the number of axles. Currently, a 54-ton limit is common for trucks with trailer in Denmark and 60-ton road trains (European Modular System) are allowed. These can also be based on a tractor/trailer combination as discussed in section 2.3.

In Sweden and Norway there are already examples of 74-ton diesel and electric trucks (74ton, 2022).

We do not include future changes in the maximum gross weight of solo trucks, because there is no indication of future legislation on this point. However, this might come after 2025.

European legislation allows in general 2 extra tons gross weight for electric and fuel cell trucks (Union, 2021).

Vehicle weight - with typical load/number of passengers (kg)

Typical vehicle weight is defined as:

Mass in running order + Average load factor [%] * Maximum payload + Average number of passengers * 70 kg

Table 9 Average utilization factors for trucks and buses in Denmark

	Average load factors for Denmark (DST/TEMA)				
	SOLO	TRAILER	SEMI	BUS	COACH
Payload	44.3%	42.7%	56.5%	18.2%	32.0%
Passengers	-	-	-	8.2	17.3
2050 Future	Unchanged	Unchanged	Unchanged	12	25

The current utilization factor for city buses is very low at 8.2 passengers. We do, however, expect this factor to increase to about 12 passengers with the introduction of more flexible bus systems, such as the need based Flextrafik. For trucks, we assume the utilization factors to be constant, but as maximum payload rises, so does the average payload.

Average payload in percent for trucks was found in (DST, 2021).

Fuel tank and/or battery size

Size of the fuel tank (in liters) can vary a lot (Mercedes-Benz, TANK VARIANTS, 2022), so a span of 400-1000 liters is assumed for diesel powertrains with semi-trailer trucks having the biggest tanks. With higher fuel efficiency expected for future powertrains the required tank size will get smaller.

Capacities of BEV batteries were collected from vehicle suppliers' websites. Different battery options are offered. Currently 300-600 kWh is the typical size (Mercedes-Benz, 2022), and it will quite certainly increase to more than 1 MWh as batteries generally get cheaper.

FCV's batteries are smaller, currently about 70 kWh. There is no technical need for bigger batteries as the range is secured by the hydrogen tanks. Currently these are about 30 kg H_2 with a potential for increasing tank pressure and using liquid hydrogen in the future. See (ICCT, 2022).

Weight of battery

Diesel trucks only have a 24V lead-acid battery, which weighs about 56 kg. Battery and fuel cell trucks have lithium-ion battery packs weighing anywhere from 500 kg to 5 tons. Current energy densities are 140-200 Wh/kg and in the future, it could be 250-400 Wh/kg (ITF, 2022). We therefore assume the following specific weights of lithium-ion battery packs now and in the future.

Table 10 Prediction of specific weight of lithium-ion battery packs

Year	2022	2050
Battery weight kg/kWh	6.1	3.8

Charging power

The charging power is measured in kW and determines the speed at which a certain battery size can be recharged. Current chargers for heavy vehicles offer up to 160 kW but there is rapid development in this parameter, so we expect 1.5 MW-level chargers in the future. The fast-charging window may be limited to 20-80% charge and may also be reduced in cold weather. This depends on the battery type.

	DC								AC		
	MCS	Tesla Megacharger	CCS-2	ChaoJ	Level 3	Volvo max.	Actros max.	Scania max.	Pantograph	3x64Amp	Level 2
Maximum power kW	3750	1500	500	900	350	250	160	130	450	43	22

Figure 40 Charging power of current and future systems for heavy duty vehicle charging (various sources).

For comparison we also calculate the corresponding kW transferred during diesel and hydrogen refilling. These are in the range of 3-5 MW for hydrogen and 20-30 MW for diesel. Diesel dispensers deliver between 60 -120 liter per minute. Hydrogen dispensers deliver 50-220 kg per hour (NEL, 2022). Refueling times in minutes for diesel, electricity and hydrogen were also discussed in (Energi, 2022).

Typical charging/refueling time

Time for charging is calculated as:

Battery capacity [kWh] / Average Charge power [kW].

This simplification has been chosen due to the great variation in charging solutions and the individual charging curves of each battery type along with the influence of temperature etc. With charging times under one hour, batteries generally need cooling and with big batteries such as in trucks so do the power cables. There is a rapid development in charging infrastructure and battery technology, so we can expect charging times under 15 minutes in the future.

Number of axles – max

The maximum number of axels for the vehicle category is important for the carrying capacity and thus an important sales parameter. It is supplied for information but is not used for calculations. The future will see up to 11 axles on mega trucks with trailers. See cover page of this report (Traficom, u.d.)

Number of axles – typical

Standard number of axels for the typical vehicle are not directly used for calculation. Currently we consider only 2, 3- 6 and 7 axles as typical.

Motor size (kW)

The size of motor is the peak power of the diesel engine or the electric traction motor in a standard vehicle within this subcategory (in kW).

Current diesel engines for heavy vehicles deliver about 230-540 kW. They can be made to suit any power requirement, but we do not foresee any drastic development of significantly larger diesel engines for these vehicle segments. Instead, hybrid powertrains are more likely to prevail.

Electric traction motors are fitted as single, twin, triple or quad motor configurations totaling about 350 kW today, but there are reports of 700+ kW motor configurations in the very near future. We expect to see electric powertrains surpass 1 MW power in the longer term.

The power of the fuel cell pack in FCV's is usually lower than the motor power, currently about 190 kW.

Motor size influences calculations because the simulation tool allows the vehicle to accelerate slower when underpowered. In other words, the distance travelled will be the same for all vehicles going through the same cycle, but the time to reach the target may increase. This is true for many of the current 2022 powertrains with 374-490 kW. To fulfil all cycles with a full payload the vehicles would need 700-800 kW, which we are assuming for all 2050 powertrains.

In the simulation tool, specific power- and torque curves for a range of engines and motors are used. A 3-speed gearbox is used for electric drivetrains and a 12-speed is used for diesel.

Vehicle length – max

Traditional road trains are limited to 18.75m and 16.5 m for semis. The maximum length of the vehicle is a matter of legislation. We expect to see road trains up to 25.5 m in near future. EMS (European Modular System) combinations may have a maximum length of 25.25. Finland allows 76-ton road trains up to 34.5 m in length. From an energy perspective, long vehicles are more efficient. The possible downsides are road safety and load on bridges, length of parking spaces etc.

A series of initiatives are taken to increase the legal length and weight of trucks in Denmark, by 2025.

Vehicle length – typical

The length of the typical bus, solo truck, or truck and trailer in each subcategory is only supplied for information. The length does not influence calculations directly because all aerodynamic effects are accounted for in the drag coefficient.

5.3. Energy and fuel related parameters

Powertrain efficiency

There is no universally accepted definition of average powertrain efficiency that includes regenerative braking. We use the definition below:

(ROLLING RESISTANCE + AERODYNAMIC DRAG) / TOTAL FUEL INPUT ENERGY

This number describes the entire power train including braking and idling losses. It is sometimes referred to as Power Train and Braking Efficiency (PABE). It is always lower than the engine efficiency because braking and idling result in losses. Effective regenerative braking adds to this efficiency, but this effect is not considered for ICE vehicles at the moment because hybrid ICE's are out of scope.

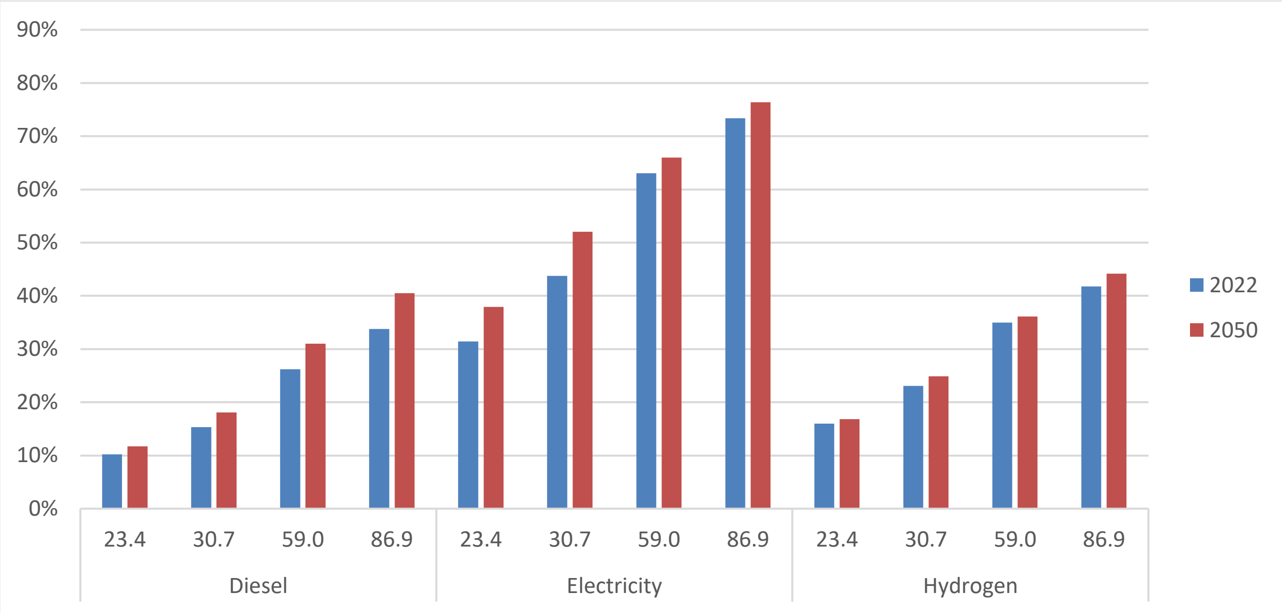

Figure 41 Predicted powertrain efficiency for all vehicles across fuel types and average driving speed in km/h.

Energy consumption

The tank-to-wheel energy consumption (MJ/km) is a result of simulation with driving simulation software (section 5.1).

We define:

MECHANICAL ENERGY = ROLLING RESISTANCE + AERODYNAMIC DRAG

GROSS ENERGY = MECHANICAL ENERGY / POWERTRAIN EFFICIENCY

The results from these simulations are summarized in a chart describing each chosen vehicle category. Note that braking energy is not included in the mechanical energy but is instead included in the powertrain efficiency.

Mechanical energy (charts)

Energy consumption at wheels was also mentioned in (Transport & Environment, 2020).

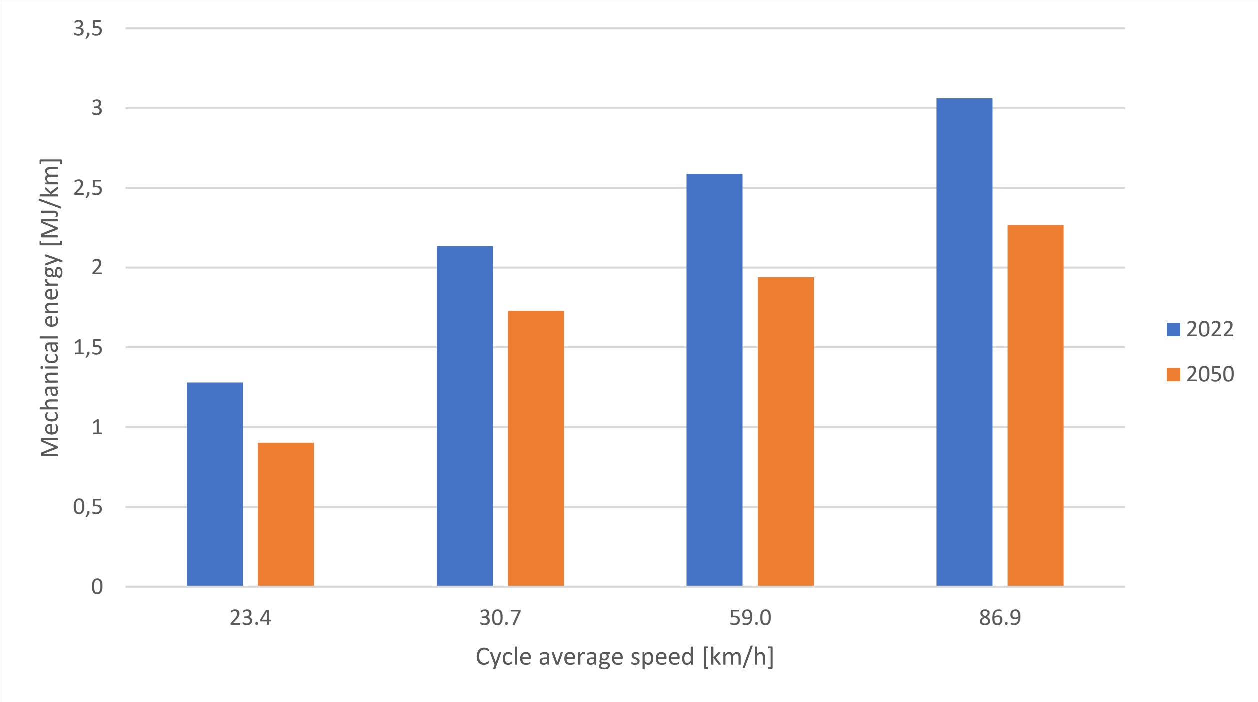

Figure 42 Mechanical energy for all fuels dependent on drive cycle average speed in km/h

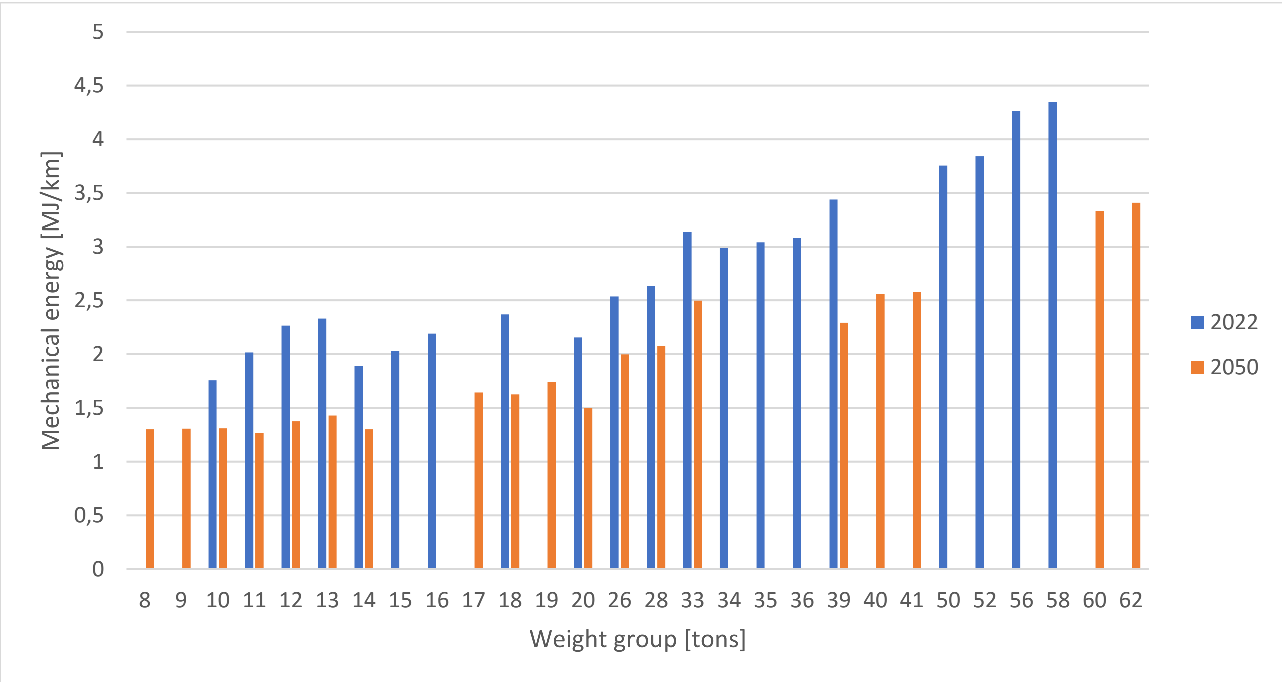

Figure 43 Mechanical energy in MJ/km for all fuels dependent on weight in tons

Gross energy (charts)

Gross energy means energy supplied with the fuel, excluding charging and filling losses.

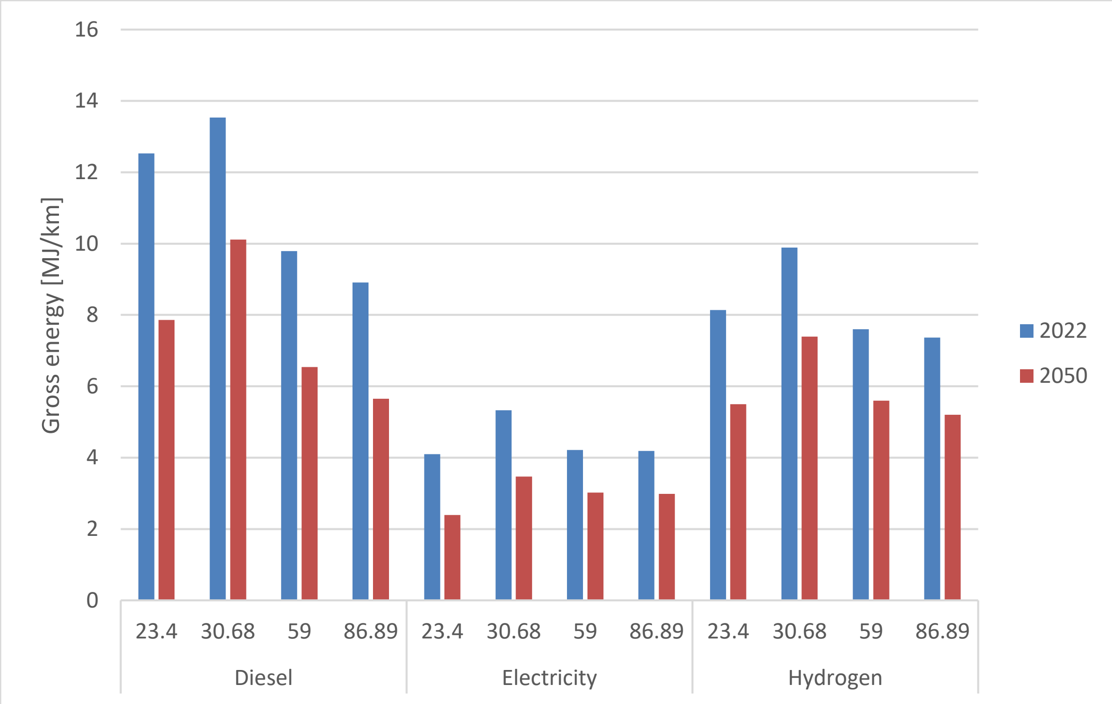

Figure 44 Predicted gross energy consumption across fuels dependent on average cycle speed in km/h.

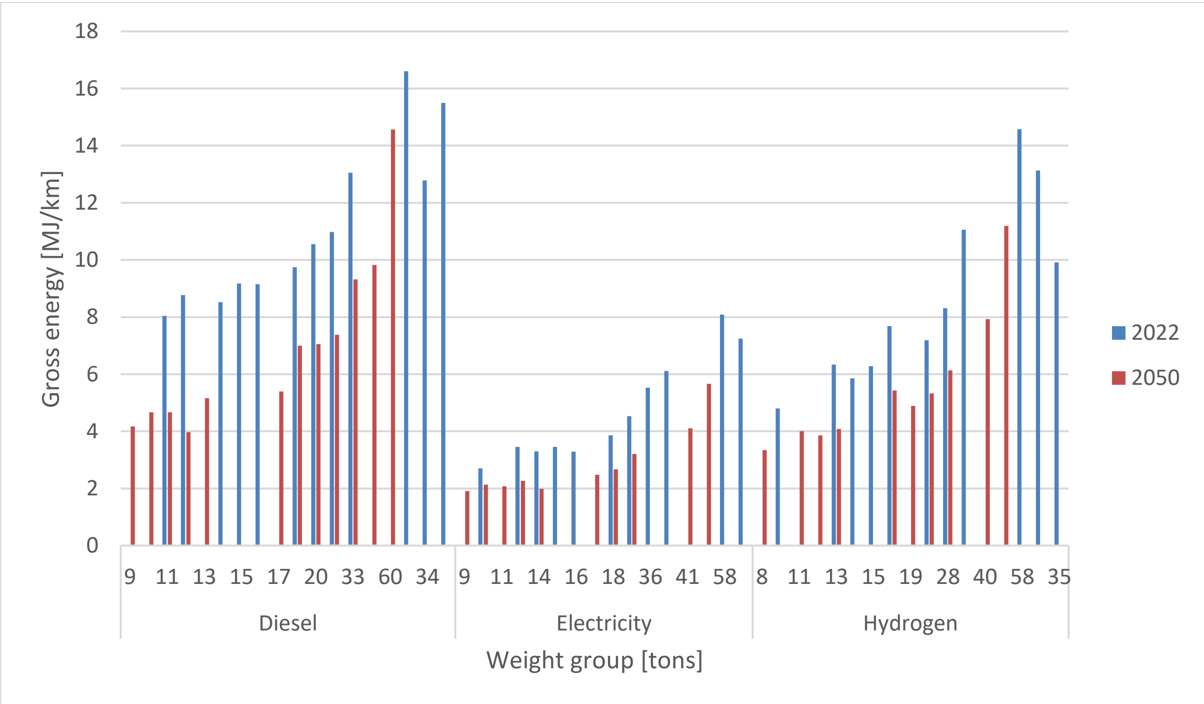

Figure 45 Predicted gross energy consumption across fuel types dependent on weight in tons.

Vehicle Range

Vehicle range (in km) for the subcategory of vehicles are calculated from the energy consumption and tank/battery size.

Seasonal variations in battery performance are not included. Cabin heating, especially relevant for buses, is not included in the calculated consumption figures.

5.4. Environment

The environmental footprints associated with heavy duty vehicles arise largely during the use phase and via their production and scrapping.

Emissions

Local emissions of CO_2, CH_4, N_2O, NO_x and SO_2 in g/km resulting from the operation of the vehicle are byproducts when driving ICE vehicles. Upstream emissions related to fuels and electricity production are not included.

Emission factors for ICE's are collected from (Lab, 2022), (Badshah, 2021). BEV and FCEV are considered zero emission and thus do not produce any direct emissions.

Diesel fuel is assigned a tank-to wheel emission factor of 74.5 gCO_2/MJ according to EN14258 (Diesel with 7% biodiesel), leading to a use-phase emission of about 370 tons (500 000 km at 10 MJ/km).

Net CO_2 emissions from production and recycling of vehicle

Emissions associated with vehicle production, scrapping and recycling are mainly collected from (Lab, 2022).

According to (Burul, 2022) an electric truck has a production phase footprint of 53.6 tons CO_2 while production of an ICE truck produces 27.5 tons CO_2. Batteries account for 74 kg CO_2 per kWh. Assessment from literature span from 30 to 494 depending on the type of battery and production country.

Buses are investigated by (Anders Nordelöf, 2019).

In general, materials for production (steel etc.) and batteries are by far the dominating factor. Materials is roughly 21-24 tons of CO_2 per vehicle. Assembly and painting emit about 0.7 tons CO_2 per vehicle. The upstream CO_2 emissions associated with the scrapping/recycling of the vehicle is roughly 0.9 tons.

Table 11 CO_2 emissions related to production and scrapping of heavy duty vehicles.

	Truck	Trailer	Bus	Battery pack
CO_2 per vehicle	30 tons	30 tons	120 tons (Anders Nordelöf, 2019)	18 tons
CO_2 per kg vehicle	3.5	3.5	9	10.5

5.5. Financial data

Typical vehicle lifetime

The economic lifetime of a truck is set to 7 years (Scania), typical technical life 10.5 – 13.8 years.

(COWI, 2016). Second-hand life of the trucks is not considered.

Typical battery lifetime

Typical life span of the battery/fuel cell (in years) depends on assumptions on charging cycles etc. A common assumption is that the battery will last as long as the vehicle. Since this is highly dependent on the number of daily charge cycles, however, some LCA analyses include one battery replacement during the vehicle lifetime.

Typical vehicle life mileage

Typical lifetime of the vehicle (in km) was collected from DTU report (COWI, 2016).

Typical # of km driven per year

Typical truck 60,000 km (Scania). Semi-trailer truck 90,000 (Transportministreiet, 2016). Max. 230,000 km (Transportministreiet, 2016). The typical span in daily mileage for tractors is about ±25%, for rigid trucks ±40% (ITF). Other factors from DTU report (COWI, 2016).

Upfront vehicle cost

The vehicle cost is divided into 3 parts:

Cost of drive train + Cost of energy storage system + Cost of chassis

Overhead cost, profit margins are included in the numbers. The main sources of information for purchase cost are: (ICCT, 2022), (Eckerle, 2015) (Carlier, 2022), (Scania, 2022).

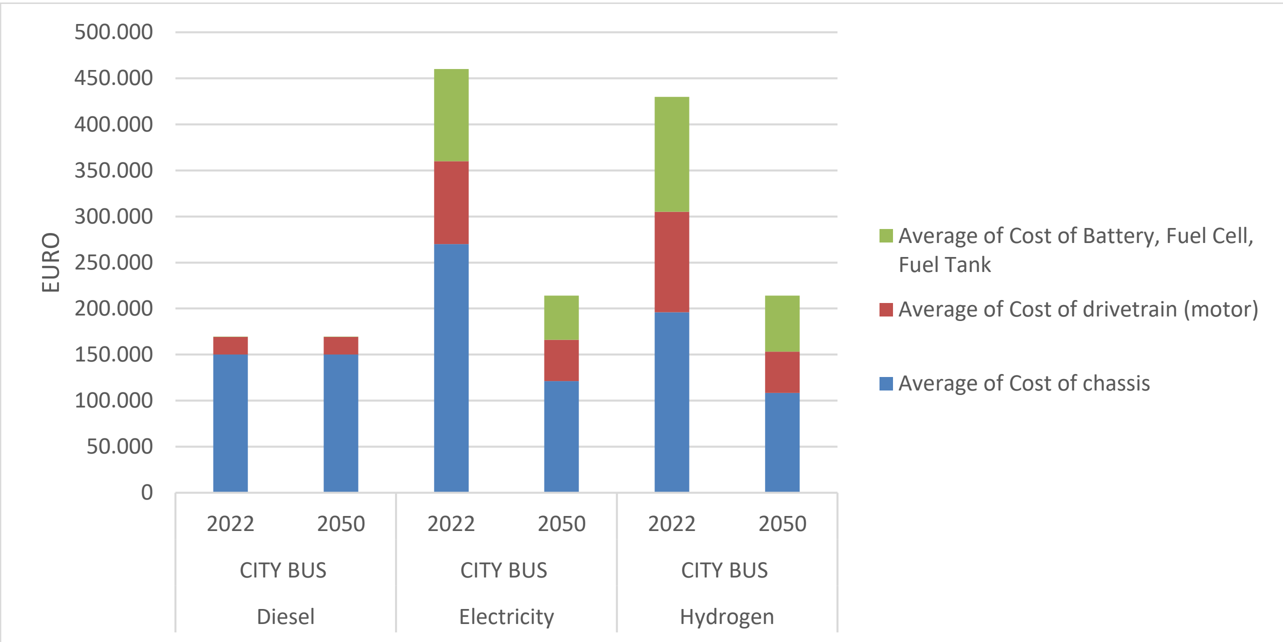

Figure 46 Predicted cost of city buses in EURO

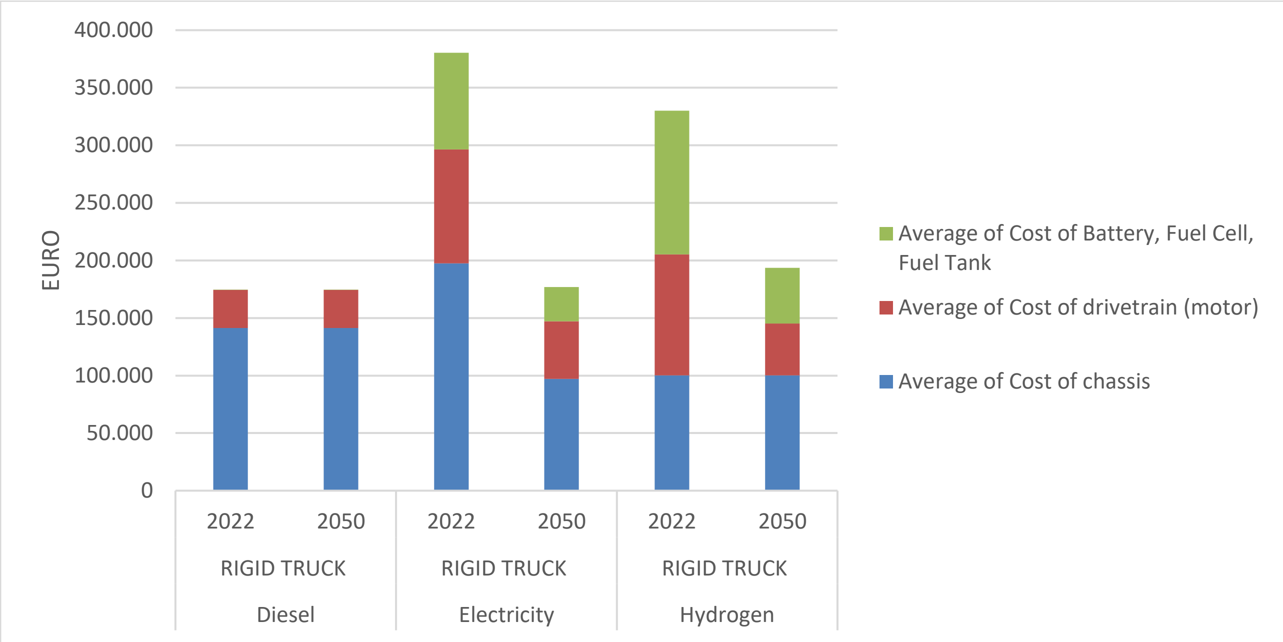

Figure 47 Predicted cost of solo trucks in EURO

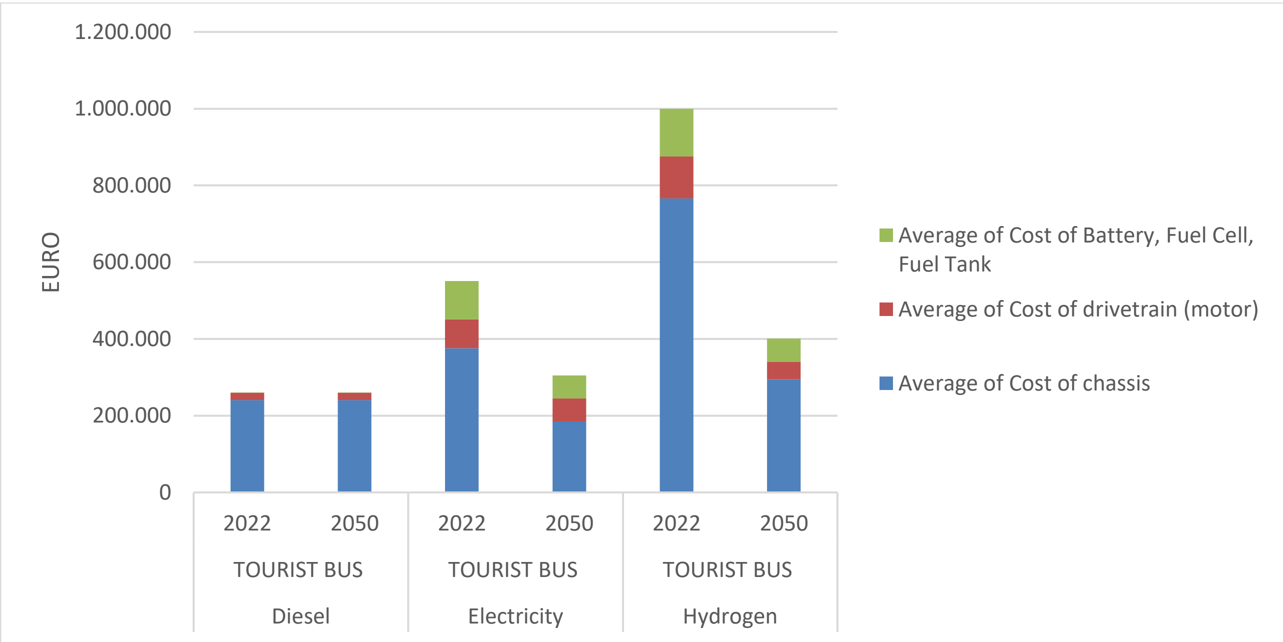

Figure 48 Predicted cost of tourist buses in EURO

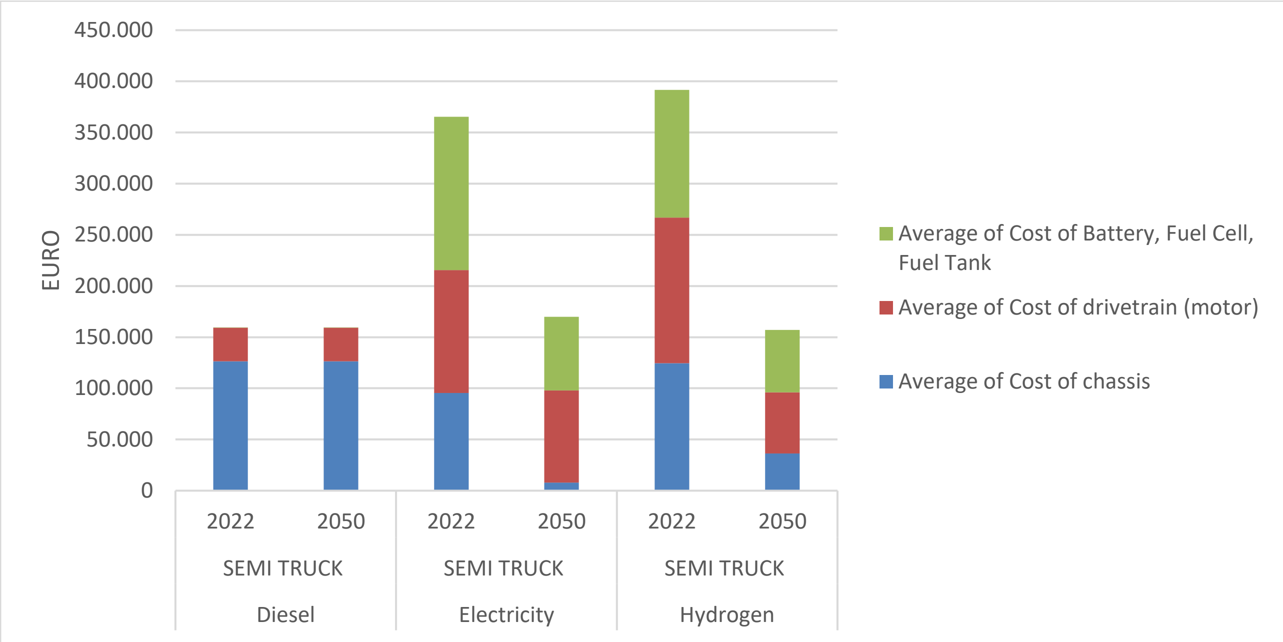

Figure 49 Predicted cost of semi-trailer trucks, based on (ITF, 2022), (ICCT, 2022)

Fixed service and maintenance (EUR/year)

Fixed service cost is the estimated total service and repair cost divided by years of operation. This can be used when the annual mileage is not known.

Fixed and variable costs shall not be added together.

The service and maintenance cost (average during the first 4 years (€/year)) are about 7200 EUR/year (Scania) for a diesel solo truck doing 60,000 km per year. Average 0.12 EUR/km. For a BEV solo truck (Scania) the total service and maintenance costs are approx. 6,400 EUR/year, average 0.107 EUR/km.

Variable service and maintenance (EUR/km)

The variable service cost is the estimated total service and repair cost divided by number of kilometers. This is to be used when the annual mileage is known.

Fixed and variable costs shall not be added together.

Existing Danish reports put the average maintenance cost of a heavy diesel vehicle at about 0.12 EUR/km (COWI, 2016).

The variable service and maintenance costs at 95,000 km/year estimated by (Berger, 2020).

Diesel: 0,072 EUR/km

Electric 0,057 EUR/km

Fuel cell: 0,064 EUR/km

Estimates for buses are at 0.40 EUR/km (diesel) and 0.36 EUR/km (electric).

6. Annex 1 – Segmentation analysis

Data sources and methodology for the segmentation analysis

As it is not possible to describe every kind of HDV, it was necessary to arrive at segments that incapsulate the most relevant vehicle types, while at the same time limiting the number of segments to a manageable number for the purpose of this catalogue.

The segmentation analysis was based of two types of sources:

1) Publicly available data on the number of HDVs, the composition of the vehicle fleet and driving patterns from i.e., Statistics Denmark.
2) Interviews with industry stakeholders. The aim was to gain knowledge about which types of powertrains are relevant within the individual segments, and which driving patterns are typical within the various segments.

The process of selecting the final segments was an interactive process consisting of:

1. Reviewing available data and discussing initial segments
2. Contacting relevant shareholders for their comments and input
3. Revising the segments and presenting them to numerous stakeholders at workshop
4. Incorporating stakeholder inputs into the final segments

The description below describes the various data that was considered. While some inputs are reflected quite clearly in the final segments, others are less so. The latter are nonetheless included in the description to provide an understanding of the data available, as well as the considerations made during the segmentation analysis.

Vehicle stock for trucks in Denmark

According to Statistics Denmark (DST), as of 2021 there were roughly 42,000 trucks with a maximum gross weight of more than 3.5 tons in Denmark (DST BIL707). 35% are semi-trailer trucks, only 4% of these trucks have a total weight between 3.5-6 tons, and the majority are trucks with a total weight of over 6 tons. Other than the smallest segment, Statistics Denmark further classified according to their type of driving, i.e., use for private hauling, corporate use, and ‘other use’. The categorization according to uses may not be relevant for the current analysis, but the evolution in the Danish stock of trucks from 2017 to 2021 according to these categories is displayed in the figure below.

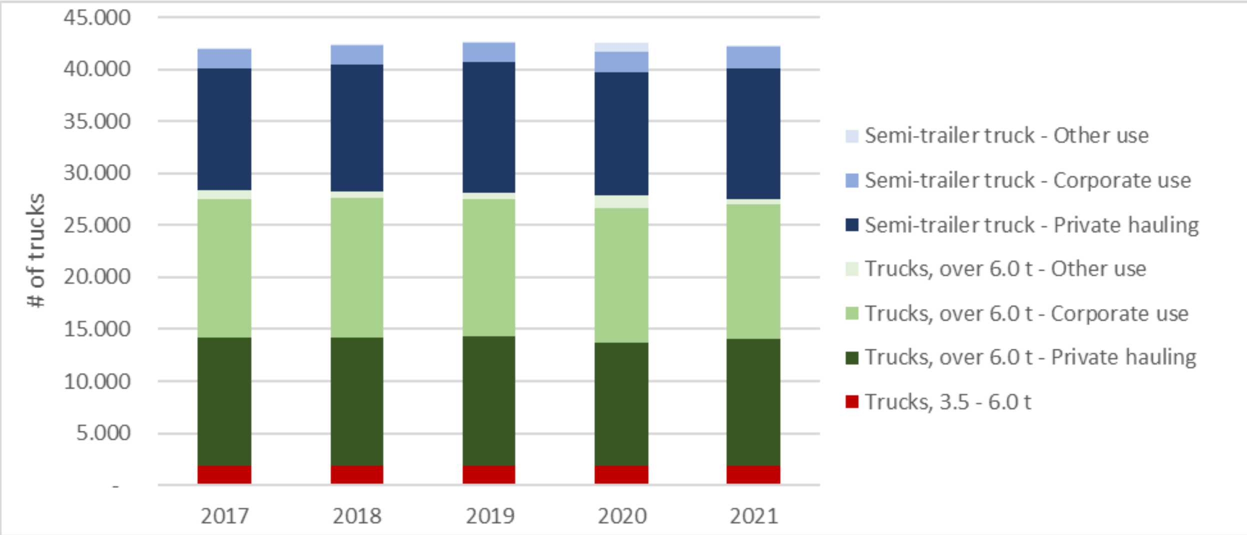

Figure 50: Evolution in the Danish stock of trucks from 2017 to 2021 (Danmarks Statistik, 2021c)

As can be seen from the figure, both the total number of trucks and the number of trucks in each segment have remained quite constant over the last 5 years.

Transport work and trip length for trucks in Denmark

To undertake meaningful transport analysis, it is necessary to be able to combine individual vehicle segment energy consumption with the amount of transport work undertaken by each vehicle segment. Statistics Denmark provides historic data on transport work for trucks with a total weight over 6 tons according to three types of trucks and/or truck and trailer combinations:

- Solo truck (i.e., without a trailer attached), which is further subdivided into 4 weight categories
- Truck with a rear-fastened trailer[6] , which is further subdivided into 3 weight categories
- Semi-trailer truck with trailer[7] , which is further subdivided into 3 weight categories

The main difference between a truck with rear-fastened trailer and a semi-trailer truck with trailer is that when they both have no trailer attached, the truck with rear fastened trailer essentially becomes a solo truck, and thus still has the weight and air and road resistance associated with the large truck, whereas the semi-trailer truck becomes considerably lighter, thus greater reducing its energy consumption per km. This difference may also result in different driving patterns as the semi-trailer truck can pick up and drop off trailers at various locations with greater ease. For these reasons this differentiation in terms of segmentation was maintained in the current catalogue.

The evolution in transport work (in millions of km) according to these segments from 2017-2020 is displayed in Figure 51.

[6] 'Påhængsvogntog' in Danish

[7] 'Sættevognstog' in Danish

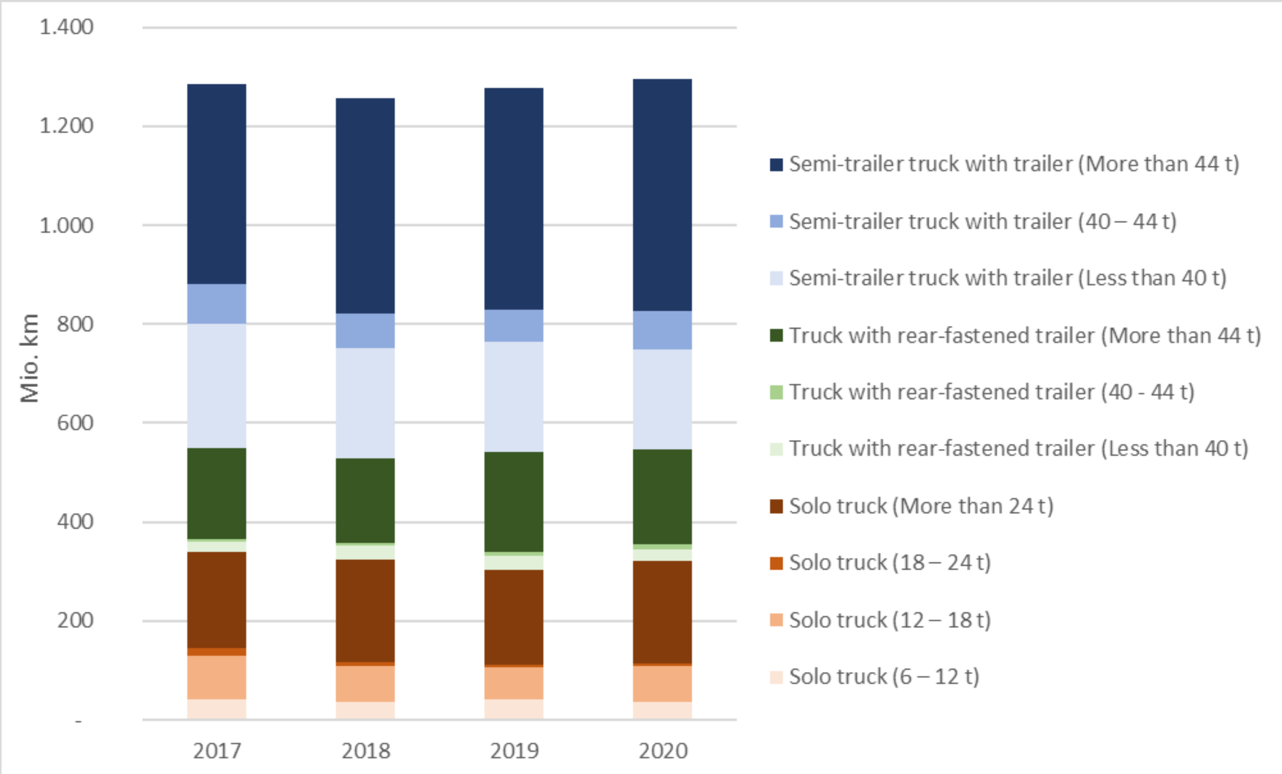

Figure 51: Evolution in Transport work (in millions of km driven) from 2017-2020 for trucks with a total weight over 6 tonnes (Danmarks Statistik, 2021a)

The figure highlights the fact that overall transport work in Denmark from 2017 to 2020 was relatively stable, while the distribution between displayed categories was also quite constant. However, there were some exceptions, most notably the segment for semi-trailer trucks with more than 44 tonnes, as this grew by over 15% over the 4-year period.

Statistics Denmark also provides data on the number of trips and trip length for the same categories as outlined above. This data is presented in the table under.

Table 12: Transport work in thousands of trips per year in 2020 (Danish trucks over 6 tonnes in total weight) (Danmarks Statistik, 2021a)

Type of truck and/or truck and trailer combination	Trip distance (km)											
	< 15	15-29	30-49	50-74	75-99	100-124	125-149	150-199	200-249	250-299	300 >	Total
Solo truck (6001 – 12,000 kg)	70	30	31	44	40	41	18	33	21	16	21	**365**
Solo truck (12,001 – 18,000 kg)	90	93	95	75	50	60	62	51	30	23	58	**687**
Solo truck (18,001 – 24,000 kg)	8	5	6	7	10	5	3	6	5	2	1	**58**
Solo truck (More than 24,000 kg)	1068	597	466	334	183	113	95	132	105	84	106	**3283**
Truck with rear-fastened trailer (Less than 40,001 kg)	18	40	28	22	22	15	12	18	32	7	10	**224**
Truck with rear-fastened trailer (40,001 – 44,000 kg)	0	1	2	2	1	1	2	7	6	8	12	**42**
Truck with rear-fastened trailer (More than 44,000 kg)	529	453	438	341	179	120	90	126	84	78	103	**2541**
Semi-trailer truck with trailer (Less than 40,001 kg)	195	121	107	130	80	58	65	99	80	146	240	**1321**
Semi-trailer truck with trailer (40,001 – 44,000 kg)	53	43	42	59	36	28	24	42	39	54	86	**506**
Semi-trailer truck with trailer (More than 44,000 kg)	508	507	559	466	303	232	190	273	175	291	430	**3934**
Total	**2539**	**1890**	**1774**	**1480**	**904**	**673**	**561**	**787**	**577**	**709**	**1067**	**12961**

Table 12 includes some truck and/or trailer segments with very few trips, as well as a large number of trip distance categories. The data has therefore been summarized into the below table which reduces the number of segments to 6 and aggregates the trip lengths into 150 km sized groups. These three transport distance categories could potentially be relevant cut-off points in terms of whether non-conventional powertrain trucks could be relied upon to serve that segment today, and in the upcoming years.

Table 13: Transport work in thousands of trips per year in 2020 (Danish trucks over 6 tonnes in total weight) (Danmarks Statistik, 2021a)

Type of truck and/or truck and trailer combination	Number of trips				% for truck type		
	Under 150 km	150-300 km	Over 300 km	Total	Under 150 km	150-300 km	Over 300 km
Solo truck up to 18 t	799	174	79	1.052	76%	17%	8%
Solo truck over 18 t	2.900	334	107	3.341	87%	10%	3%

Truck with rear-fastened trailer under 44 t	166	78	22	266	62%	29%	8%
Truck with rear-fastened trailer over 44 t	2.150	288	103	2.541	85%	11%	4%
Semi-trailer truck with trailer under 44 t	1.041	460	326	1.827	57%	25%	18%
Semi-trailer truck with trailer over 44 t	2.765	739	430	3.934	70%	19%	11%
Total	**9.821**	**2.073**	**1.067**	**12.961**	**76%**	**16%**	**8%**

Table 13 highlights the fact that the majority of trips for all sizes of trucks is under 150 km, with only 8% of all trips being over 300 km. However, when looking at the amount of transport work undertaken (Table 14 below), while there are differences according to truck segment, it is interesting to note that total transport km is almost divided evenly between the 3 distance categories.

Table 14: Transport work in millions of km driven per year (Danish trucks over 6 tonnes in total weight) (Danmarks Statistik, 2021a)

Type of truck and/or truck and trailer combination	Transport work in millions of km				% for truck type		
	Under 150 km	150-300 km	Over 300 km	Total	Under 150 km	150-300 km	Over 300 km
Solo truck up to 18 t	45	36	29	110	41%	33%	26%
Solo truck over 18 t	100	71	39	210	48%	34%	18%
Truck with rear-fastened trailer under 44 t	9	17	9	35	27%	48%	25%
Truck with rear-fastened trailer over 44 t	92	61	38	191	48%	32%	20%
Semi-trailer truck with trailer under 44 t	54	104	122	281	19%	37%	44%
Semi-trailer truck with trailer over 44 t	142	164	162	468	30%	35%	35%
Total	**443**	**453**	**399**	**1.296**	**34%**	**35%**	**31%**

Stakeholder inputs and data

As there are different driving needs within the segmentations from Statistics Denmark, various stakeholders within the industry were contacted for their input on potentially relevant aspects to be reflected in the final segments. This dialogue with industry professionals led to a preliminary segmentation as outlined in Table 15. This segmentation took into account differences in 1) weight, 2) driving patterns and 3) application. The number of registered vehicles is based on an extract from Bilstatistik (Car Statistics). Lastly, typical annual mileage estimates, as assessed by a leading truck manufacturer, were also included. Typical values, as opposed to average figures, were utilised as they encompass haulers that use their vehicles a great deal.

Table 15: Preliminary segmentation (Bilstatistik, 2021)

#	Description	# of axles	Max. total weight (tonne)	Max. road train weight (tonne)	Typical km per year	# of registered vehicles*
1	Small trucks (e.g., municipal vehicles)	2	7.2	N/A	60,000	2,788
2	Medium trucks (national and regional distribution)	2	17.9	N/A	80,000	6,959

3	Box truck with lift with or without refrigeration system	2	18	N/A	80,000	3,464
4	Box truck with lift with or without refrigeration system	3	26	N/A	80,000	4,872
5	Fixed bed truck with crane (e.g., used for scaffolding or delivery of building materials)	3	26	N/A	60,000	1,746
6	Container trucks and trucks with a hook lift hoist	4+3	32	56	100,000	5,982
7	Semi-trailer truck (largely for international transport)	2	N/A	40	160,000	3,547
8	Semi-trailer truck (regional and national transport)	2	N/A	40	120,000	7,435
9	Tankers and other trucks used for hauling heavy goods such as animal feed	4+3 or 3+4	26 or 32	56	120,000	3,500**
10	Municipal solid waste truck	3	26	N/A	25,000	1,546

*Notes: *The total number of trucks (33,000) covers the vehicle stock from 16 tonnes and up. It is therefore lower than the number calculated in DST (42,000) with a difference of approx. 11,000 more trucks in DST. This is because data from DST calculates the number of trucks over 3.5 tonnes.** It was not possible to calculate the number of "Tankers and other trucks used for hauling heavy goods" (cat. 9), as the Car Statistics includes this as a subset for category 8, semi-trailer tractor for national / regional distribution. The 3500 value is thus an estimate*.

Over 25 relevant stakeholders met at workshop during October of 2021 to discuss potential vehicle segments, and the above suggested categories were presented to kickstart the discussion.

Final truck segments

In arriving at the final truck segments, given the importance of having available data for transport work, the segmentation according to Statistics Denmark illustrated in Figure 51 played a significant role. However, due to a ambition to have a reasonable number of segments to work with and present, it was assessed that for both truck and trailer categories it could be possible to place the 40-44 tonne segment with the less than 44 tonne segments without losing too much detail. In addition, inputs from relevant stakeholders, as well as data on the current vehicle stock, suggested the need for a segment for trucks less than 6 tonnes, as well as a separate segment for municipal solid waste trucks. The resulting truck segmentation is displayed in the table below.

Table 16: Truck segmentation

Category #	Type of truck and/or truck and trailer combination
1	Solo trucks up to 6,000 kg
2	Solo trucks 6,001 – 12,000 kg
3	Solo trucks 12,001 – 18,000 kg
4	Solo trucks 18,001 – 24,000 kg
5	Solo trucks over 24,000 kg
6	Truck with rear-fastened trailer up to 44 t

7	Truck with rear-fastened trailer over 44 t
8	Semi-trailer truck with trailer up to 44 t
9	Semi-trailer truck with trailer over 44 t
10	Municipal solid waste truck

Vehicle stock and driving patterns for buses in Denmark

According to Statistics Denmark, there were roughly 12,300 registered buses in Denmark as of Jan 1st, 2021. The evolution in the number of registered buses according to vehicle weight since 2011 is displayed in Figure 52.

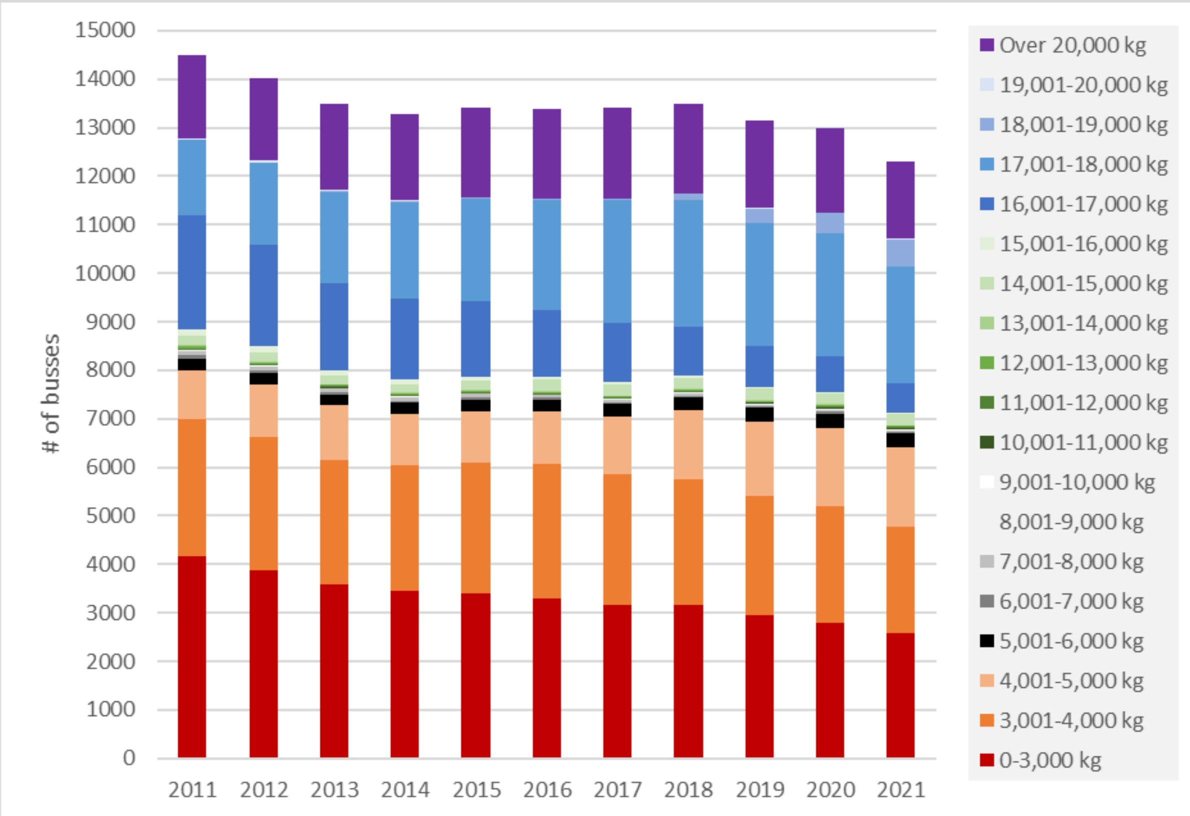

Figure 52: Evolution in the number of registered buses according to vehicle weight in Denmark since 2011. (Danmarks Statistic, 2021b)

The key takeaways from Figure 52 are that the total number of registered buses in Denmark has been falling over the past decade, and that while there are many weight categories displayed (19 in total), the vast majority can be found within 7 categories with a minimum of 500 buses each. Despite comprising 11 individual categories in the figure (depicted in black, grey, white and various shades of green), buses weighing between 5 and 16 tonnes represented less than 6% of all registered buses on Jan 1st, 2021, and less than 7.5% of all buses over 3 tonnes.

Table 17 illustrates how Danish bus registrations have evolved since 2016 in terms of the powertrain type. As of the start of 2021, 0.7% of buses were electric, 1.4% were gas powered, 2.7% were petrol (nearly all petrol buses were under 4 tonnes, and they comprised 6.5% of all buses under 4 tonnes), and the remaining 95.2% were diesel powered. While only 0.7% of registered buses were electric in 2021, this is up from 0,05% in 2019, and very strong growth is expected to continue, particularly as a number of municipalities have tendering procedures that are aimed at zero or very low emission buses.

Table 17: Evolution in the number of registered buses according to powertrain type in Denmark since 2016. (Statistics Denmark, Table 2021b), note that status by end of 2022 has not yet been published by Statistics Denmark. The stock of electric buses have increased to approx. 700.

	2016	2017	2018	2019	2020	2021
Petrol	529	478	437	396	363	328
Diesel	12,814	12,857	12,883	12,599	12,399	11,704
Gas	33	74	155	155	155	170
Electric	4	6	5	7	86	92
Hydrogen	0	0	0	0	0	3
Plug-in Hybrid	1	1	1	1	0	1
Other	2	1	1	0	0	0
Total	13,383	13,417	13,482	13,158	13,003	12,298

The above table provided insight into which powertrain types would be relevant to include in the datasheets.

Final bus segments

The selected 5 bus segments according to weight for buses weighing more than 3 tonnes are displayed in the table below (as the current catalogue covers heavy road transport, vehicles classified as buses but weighing less than 3 tonnes were not included).

Table 18: Bus segmentation - weight

Category #	Bus type	% of registered buses on Jan 1st, 2021 over 3 tonnes	Weight categories Figure 52
1	Buses 3,001 – 5,000 kg	39.4%	2 - Orange
2	Buses 5,001 – 10,000 kg	3.8%	5 - Black, grey, white
3	Buses 10,001 – 16,000 kg	3.4%	6 - Green
4	Buses 16,001 – 20,000 kg	36.8%	4 - Blue
5	Buses over 20,001 kg	16.4%	1 - Purple

Categories 2 & 3 encompass buses with very large variations in size and weight. However, as highlighted in the table above, they account for few of the total number of registered buses in Denmark. It will be up to the chapter authors to select a representative bus size for these categories, and if deemed necessary, provide information and data sheets for more than one bus size.

Subcategories for buses

Statistics Denmark divides registered buses into two main categories, buses for route services (rutekørsel in Danish, and also sometimes referred to as city buses) and buses for tourist services (turistkørsel in Danish, and sometimes referred to as coaches). A small number of buses are also allocated into a 3rd category entitled tourist/rental (turistkørsel/udlejning in Danish). The development in registered buses according to these categories is displayed in Figure 53, and it can be seen that roughly 57% of registered buses are currently used for route services and the remaining 43% for tourist services.

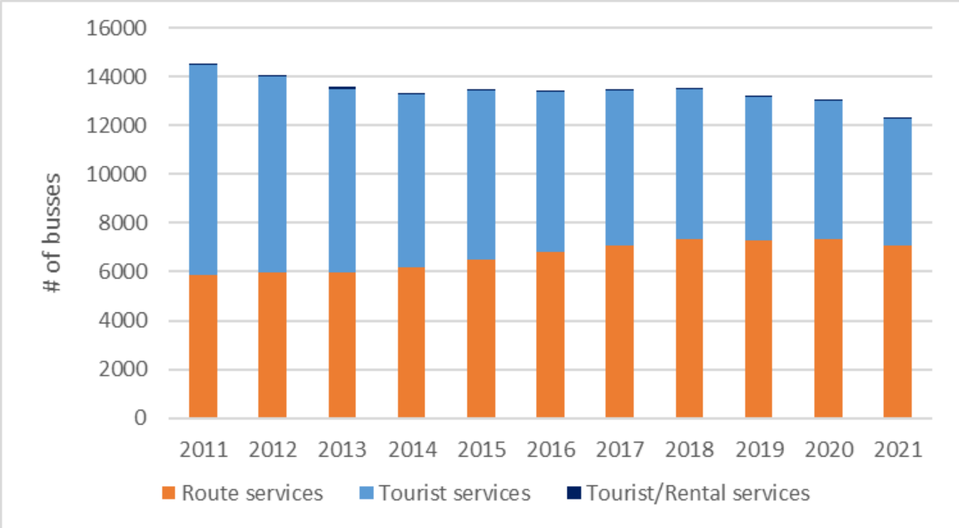

Figure 53: Evolution in the number of registered buses according to use in Denmark since 2011. (Danmarks Statistik, 2021c), note that the number includes both large and small buses.

In terms of total annual km driven, for the years 2017-2019, Danish buses averaged 640 million km. Unfortunately, there is currently no available data regarding the distribution between route and tourist services from Statistics Denmark, but the assumptions on which the Danish Energy Agency's Climate Projection is based show that route buses account for approx. 70% of the traffic work.

Denmark's largest transport company, Movia, works with 3 overall segments: City buses, city buses in the province/ suburbs and what is roughly translated as 'highway buses' (landevejsbusser). An initial dialogue with Movia, however, indicates that the last two segments may be merged, as the driving patterns are not significantly different.

Based on the available data, and discussions with various stakeholders, it is suggested to have two subcategories for each of the 5 bus weight segments: a) Route buses b) tourist buses. The primary reason for this distinction is that these two types of buses can have very different driving patterns, costs, and designs. For some bus segments it may not be necessary to provide data and information on both types, in which case the chapter authors can describe why this is not necessary. On the other hand, for some weight segments it may be relevant to include a 3rd hybrid subcategory similar to what Movia described above, e.g., route buses that operate in the provinces.

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