Making zero-emission trucking a reality

Truck Study 2020: Routes to decarbonizing commercial vehicles

Dr. Jörn Neuhausen, Dr. Christian Foltz, Dr. Philipp Rose, Felix Andre
Electrification of trucks is an imperative for the next decade. In 2030, more than 30% of all European trucks will be zero-emission.

Zero-emission trucks are the future
Electrification of trucks is an imperative. Zero-emission light-duty trucks (LDT) are becoming cost competitive, while heavy-duty trucks (HDT) in long-haul applications pose a high Total-Cost-of-Ownership (TCO) risk.

Multiple technologies compete
For HDTs, no zero-emission technology can replace the diesel truck easily. While electric alternatives with Battery and Fuel Cell seem promising, Catenary appears unattractive due to high upfront infrastructure investments and Synfuels might complement as an admixture.

Zero-emission trucking can compete on cost
OEMs need to focus on technological development and industrialization of Battery and Fuel Cell trucks. To reach TCO competitiveness with fossil fueled HDTs, low energy prices and long-life batteries are key.

Significant market diffusion starting 2025
Sales of electric LDTs will gain significant market share from 2025 onwards, while zero-emission HDTs will strongly diffuse from 2030 onwards.
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OEMs must electrify their full truck portfolio because they are a major contributors to road transport CO$_2$ emissions.

**External pressure**

Commercial vehicle makers (OEMs) are under pressure to electrify their truck portfolio in order to comply with environmental regulations. European regulation force truck manufacturers to reduce their new fleet emissions by at least 30% by 2030.

**Transparency and sustainability**

A closer look at the greenhouse gas emissions in the various truck segments shows that heavy-duty trucks are accountable for roughly 66% of the CO$_2$ emissions in the road freight transport sector in Germany. Hence, electrification of these vehicles is of highest importance.

**Electrification of long-haul as main challenge**

From a technological perspective, electrification of trucks becomes more difficult with increasing range requirements combined with high gross vehicle weight. Hence, decarbonization of long-haul heavy-duty trucks emerges as main challenge.
Trucks cause a large share of global CO$_2$ emissions – heavy-duty trucks cause 66% of the road transport CO$_2$ emissions in Germany

Global gas emissions and evolution in major markets

**Global anthropogenic CO$_2$ emissions**

- In Gigatons CO$_2$
  - Other: 6.5 (17%)
  - Road transport: 31.5 (83%)
    - Passenger cars: 2.8
    - Trucks: 0.5
      - Light-duty trucks (< 3.5t): 1.1
      - Medium-duty trucks (3.5t – 15t): 1.1
      - Heavy-duty trucks (> 15t): 2.1

**Truck fleet, mileage, and emissions in Germany**

- Total fleet [vehicles]
  - Passenger cars: 14%
  - Trucks: 12%
  - Other: 5%

- Total mileage [billion vehicle-km]
  - Passenger cars: 74%
  - Trucks: 39%
  - Other: 5%

- Total emission [Mt CO$_2$e/a]
  - Passenger cars: 56%
  - Trucks: 66%
  - Other: 14%

**Key facts**

- **Global truck transport**
  - causes 3.7 gigatons of CO$_2$ emissions per year

- **In Germany**
  - the truck vehicle stock comprises about 2.7 million vehicles, of which the majority (74%) are light-duty vehicles

- However, **heavy-duty trucks**
  - account for 39% of the total mileage and 66% of the total emissions

Highly complex EU emissions regulations force OEMs to electrify heavy-duty trucks to reach ambitious emission targets by 2030

**European Union emissions regulation and the effect on long-haul heavy-duty truck emissions**

**European union emission regulation for heavy-duty trucks**

- **Baseline 2019**: 56.5 g CO₂e/t km
- **ICE efficiency/hybridization**
  - **15% Target 2025**: 48.0 g CO₂e/t km
  - **30% Target 2030**: 39.6 g CO₂e/t km
- **-50% Threshold**: 28.3 g CO₂e/t km
- **Low-emission vehicles**

**Key facts on emission regulation**

- **Reduction** of average CO₂ emissions from new heavy-duty trucks by 15% in 2025 and by 30% in 2030, both relative to a **2019 baseline**
- **4 out of 18 vehicle groups** are **regulated** and divided in **sub-groups** to account for different use **profiles**, such as **urban**, **regional**, or **long-haul**
- **Sub-group segmentation** is **based** on **cabin type** and **engine power**
- **Incentives** for zero- and low-emission vehicles
- **Mileage** and **payload weighting factors** are used for the calculation of the **total fleet emission**
- **Certain sub-groups** are **weighted higher** than other sub-groups to reflect for specific mileages and respective CO₂ impact
- From 2025 to 2029, manufacturers are required to **pay a per-vehicle penalty** of up to 4,250 € for each g CO₂/t km of excess emissions. This penalty will **increase to 6,800€** for each g CO₂/t km from 2030 onwards.

Source: EU (2019), Strategy & analysis

* Numbers are based on preliminary baseline (see ACEA, 2020)

September 2020
Multiple cities and states have already committed to ban fossil fuel trucks from either entering certain areas or charge heavily for access.

Local regulations and exemplary deep dives

**RIGA**
Access regulation
- Vehicles over 5 tons are only allowed during specified time intervals on specified streets in Riga.

**LONDON**
Access regulated payments
- Up to £14 daily charge
- Up to £300 charge if emission standards not met

**Paris**
Pollution emergency
- Emergency scheme becomes active during times of high pollution
- Vehicle ban can also be implemented for vehicles over 3.5 t. Vehicles over 3.5 t would be banned from the city.

**KRAKÓW**
Low emission zone
- In the city centre of Kraków
- Applies to all vehicles except electric, hydrogen, and gas vehicles

Key observations
- Multiple cities and states have already approved various regulations to restrict access for trucks to metropolitan areas.
- The majority of these regulations cover heavy-duty trucks e.g. access regulations (such as Riga) or urban toll roads (such as London).
- However, the impact of these regulations on long-haul HDT is fairly low, as HDTs typically head for hubs.
Each truck segment has different use cases with varying user requirements – electrification for long-haul applications most challenging

Use cases of trucks

<table>
<thead>
<tr>
<th>Truck segment</th>
<th>LDT</th>
<th>MDT</th>
<th>HDT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exemplary use case</strong></td>
<td>Crafts</td>
<td>Municipal</td>
<td>Garbage</td>
</tr>
<tr>
<td>Crafts</td>
<td>Urban Cargo</td>
<td>Municipal</td>
<td>Garbage</td>
</tr>
<tr>
<td><strong>Typical vehicle</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>• Small commercial vehicles, mostly used by SMEs</td>
<td>• Mostly used to carry parcels and mail</td>
<td>• Used for town services • Mostly utility work, public works and road maintenance</td>
</tr>
<tr>
<td><strong>Geographic reach</strong></td>
<td>• Intra-regional transport of goods and/or materials</td>
<td>• Transport within the same city and its suburban area</td>
<td>• Transport within the same city and its suburban area</td>
</tr>
<tr>
<td><strong>Typical daily range profile (km)</strong></td>
<td>&lt;200</td>
<td>200-400</td>
<td></td>
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<tr>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Low technical feasibility for electrification</strong></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Source: ETIplus data, Eurostat data, komDRIVE (2016), Strategy & analysis
Four main powertrain technology options exist to decarbonize heavy-duty trucks. However, there is no silver bullet to replace fossil diesel in every respect.

Options to decarbonize heavy-duty trucks

Currently, four alternative powertrain options are in discussion to decarbonize heavy-duty trucks: overhead catenary trucks (CAT), hydrogen-powered fuel cell electric trucks (FCT), purely battery electric trucks (BET) and combustion engine trucks that run on synthetic fuels (SYT).

Each option has varying advantages ...

Each of these technologies has different advantages compared with fossil diesel. The BET and CAT technology have unreached well-to-wheel efficiencies of 70 percent or higher. The CAT and SYT technologies gain points on the comparatively affordable powertrain and thus total vehicle cost. The FCT technology ranges somewhere in the middle compared with the other options.

... but also varying disadvantages

Undeniably, all alternative powertrain technologies face disadvantages compared to a fossil fuel powertrain. SYT technology is relatively inefficient, while BET and FCT technologies are far more expensive.
Four green technology options exist to decarbonize heavy-duty trucks: Battery Electric, Catenary, Fuel Cell and SynFuel-ICE

**Powertrain options for heavy-duty trucks: Overview**

<table>
<thead>
<tr>
<th>Truck segment</th>
<th>LDT</th>
<th>MDT</th>
<th>HDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use case</td>
<td>Crafts</td>
<td>Urban Cargo</td>
<td>Municipal</td>
</tr>
</tbody>
</table>

**Alternative powertrain options**

- **Conventional combustion engine trucks (SYT)**
  Conversion of electricity into carbonaceous fuel or "synthetic fuel" (Power-to-Liquid or Power-to-Gas); internal combustion engine used for propulsion.*

- **Purely battery electric truck (BET)**
  Direct use of electricity in electric motor for propulsion; battery used as energy storage.

- **Hydrogen-powered fuel cell trucks (FCT)**
  Conversion of electricity into hydrogen; fuel cell to transfer hydrogen into electricity to be used in electric motor for propulsion.

- **Overhead catenary hybrid trucks (CAT)**
  Direct use of electricity in electric motor for propulsion; small battery used as energy storage as main energy transferred via catenary.

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* In this study, we assume a synthetic diesel fuel that is produced CO2 neutral e.g. through CO2 extraction from the air.
There is no carbon-neutral silver bullet to replace fossil-fueled ICE as all alternatives exhibit disadvantages in different criteria

Powertrain options for trucks: Typical characteristics and evaluation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ICE</th>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economic</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Vehicle investment</td>
<td>🟢</td>
<td>🟡</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
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<tr>
<td><strong>Technological</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Loading capacity</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
<td>🟢</td>
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<tr>
<td>Range</td>
<td>🟢</td>
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<tr>
<td><strong>Ecological</strong></td>
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<td>CO₂</td>
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<tr>
<td>Public acceptance</td>
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</tr>
</tbody>
</table>

Characterization per powertrain

- **ICE – Internal Combustion Engine truck**

  “The environmental black sheep with long range.”

  “The clean version of traditional ICE with high energy demand.”

  “The most efficient lower range option.”

  “The alternative long range option with sector coupling.”

  “The very efficient underdog.”

1) In comparison to user requirements
**HDT with alternative powertrains translate into additional vehicle investments; BET and FCT cost around 60 k€ more than ICE in 2030**

**Powertrain options for trucks: Techno-economic characteristics**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ICE</th>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
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</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td>300 kW</td>
<td>300 kW</td>
<td>300 kW</td>
<td>300 kW*</td>
<td>300 kW</td>
</tr>
<tr>
<td><strong>Energy on board</strong></td>
<td>700 liter (Diesel)</td>
<td>700 liter (SynFuel)</td>
<td>500 kWh</td>
<td>60 kg (hydrogen) + 50 kWh</td>
<td>100 kWh</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>1,500 – 2,000 km</td>
<td>1,500 – 2,000 km</td>
<td>400 – 500 km</td>
<td>700 – 800 km</td>
<td>Depends on infrastructure [Independent: 40 – 80 km]</td>
</tr>
<tr>
<td><strong>Powertrain weight</strong></td>
<td>2,200 kg</td>
<td>2,200 kg</td>
<td>4,300 kg</td>
<td>2,300 kg</td>
<td>1,100 kg</td>
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### Vehicle price evolution (€)

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</thead>
<tbody>
<tr>
<td>2020</td>
<td>79</td>
<td>83</td>
<td>88</td>
<td>79</td>
<td>83</td>
<td>88</td>
<td>192</td>
<td>166</td>
<td>154</td>
<td>235</td>
<td>161</td>
<td>145</td>
<td>107</td>
<td>95</td>
<td>89</td>
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<tr>
<td>2025</td>
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<td>2030</td>
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</tbody>
</table>

*thereof 200kW fuel cell

**Making zero-emission trucking a reality**

*Source: Strategy& analysis*

**Hydrogen is stored at 700 bar**

**SynFuel – synthetic diesel fuel**

**Powertrain cost in k€**

**On-costs vs ICE 2030**

**September 2020**
Only a small amount of new refueling and/or recharging infrastructures will be required across Europe. However, alternative fuel prices will be more competitive in 2030 with a significant CO₂ tax on fossil fuels.

Few new PoS infrastructures required for Europe
To supply alternative powered heavy-duty trucks in Europe, only a limited number of new point-of-supply (PoS) infrastructures is required. In Europe, a high-demand scenario shows a need for less than 1,500 stations¹ – depending on the technology.

Different PoS infrastructure ramp-up approaches
During ramp-up of alternative PoS infrastructures, the nature of different technologies becomes apparent: While high-power charging and hydrogen refueling station networks can be built up iterative along with market diffusion, overhead catenary lines are a prerequisite and thus need large upfront installation.

Energy demand and cost vary significantly
Due to the varying efficiencies of the alternative powertrain options, the total energy demand of a high-demand scenario differs significantly. A high-demand scenario of technologies with direct electricity use (BET and CAT) would require about 80% less electricity than SYT. In a most-likely scenario, we determine the fuel prices of new technologies to be more competitive in 2030 with a significant CO₂ tax on fossil diesel fuel beyond 55 €/t CO₂.

¹) This analysis is based on a state-of-the-art optimization model to determine station location networks. For more information, we refer to Rose (2020) DOI: 10.5445/IR/1000119521
European HDT traffic mainly occurs on highways and accounts for 86 bn vehicle kilometers annually – Germany with most HDT activity of all countries

HDT traffic in Europe and Germany

**Europe**
- HDT Traffic on European Highways (in vehicles per year)
  - 1-20,000
  - 20,000-40,000
  - 40,000-80,000
  - 80,000-100,000
  - > 100,000

**Observations**
- **86 billion kilometers annually** driven by all European HDTs
- Typical **trip lengths** between **300 to 500 kilometers** across Europe
- **Traffic volume of up to 100,000 vehicles** on certain sections of road each year
- **Main traffic** occurs in **Central Europe** (Benelux, France and Germany)
- **Less traffic** in **East European countries**
- **Traffic volume is growing** by about 2% per year

The new alternative infrastructure options for HDTs are High-Power-Chargers, Hydrogen Refueling Stations and Overhead Catenary Lines

### Infrastructure options for alternative HDTs

<table>
<thead>
<tr>
<th>Visualization</th>
<th>BET – High Power Charger (HPC)</th>
<th>FCT – Hydrogen Refueling Station (HRS)</th>
<th>CAT – Overhead catenary lines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed</strong></td>
<td>Charging speed up to ~900 km/h</td>
<td>Refueling speed up to ~3,400 km/h</td>
<td>Charging speed up to ~300 km/h</td>
</tr>
<tr>
<td><strong>Refill duration</strong></td>
<td>Full charge of ca. 400 km range in about 30 min</td>
<td>Hydrogen filling of ca. 700 km range at 700bar in about 15 minutes</td>
<td>Continuous charging while driving</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Power up to 1.0 MW per charger</td>
<td>Filling capacity up to 3 kg hydrogen per minute per dispenser</td>
<td>Power up to 350 kW per HDT</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Large stations to refuel 600 HDTs per day with 30 chargers require investment of approx. 21 million € per station</td>
<td>Large stations to refuel 600 HDTs per day with 16 dispensers require investment of approx. 32 million € per station</td>
<td>Investment of 1.7 million € per km in both directions</td>
</tr>
</tbody>
</table>

Source: Oeko Institute (2018), Strategy& analysis
During ramp-up of new HDT infrastructure, investments for Catenary Lines to enable first cross-European trips are highest among alternatives

### Ramp-up of alternative HDI infrastructure for Europe

<table>
<thead>
<tr>
<th>Ramp-up stage</th>
<th>Description</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pilot network</td>
<td>Pilot projects with focus on areas with high traffic volumes (&gt; 100,000 HDTs annually)</td>
<td>0.7 bn € (35 HPC)</td>
<td>0.6 bn € (20 HRS)</td>
<td>2.7 bn € (1,600 km)</td>
</tr>
<tr>
<td>2 Area-coverage network</td>
<td>Complete coverage of Europe as a consistent network</td>
<td>2.5 bn € (120 HPC)</td>
<td>2.2 bn € (70 HRS)</td>
<td>36.2 bn € (21,500 km)</td>
</tr>
<tr>
<td>3 High-demand network</td>
<td>Complete coverage of Europe with sufficient capacity</td>
<td>29.5 bn € (1,400 HPC)</td>
<td>29.4 bn € (920 HRS)</td>
<td>44.1 bn € (21,500 km)</td>
</tr>
</tbody>
</table>

The demand-covering infrastructure networks were derived with an optimization model (NC-FRLM). For more information we refer to Rose (2020) and cover about 80% of European HDT traffic.
If all HDT traffic on European highways switched to only one technology option, the required alternative infrastructures would look quite different. High-demand network: Point-of-Supply (PoS) infrastructures for alternative HDTs on European highways.

- **SYT**: Installation of about 1,400 HPC stations required.
- **BET**: Installation of about 920 HDT-HRS required.
- **FCT**: Installation of about 21,500 km of overhead lines required.
- **CAT**: Installation of about 2,400 conventional highway stations required.

The demand-covering infrastructure networks were derived with an optimization model (NC-FRLM). For more information we refer to Rose (2020). The high-demand scenarios cover about 80% of European HDT traffic.
However, the investment into supply infrastructure is only a small share compared with the cost to produce the extra electricity required.

### High-demand network: Additional electricity demand and fix cost estimation of investments (bn €)

<table>
<thead>
<tr>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Additional demand for electricity (TWh)</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>600</td>
<td>90</td>
<td>220</td>
<td>80</td>
</tr>
</tbody>
</table>

**Energy production, storage and distribution**

- SYT: 375 (100 renewable, 260 storage, 15 distribution)
- BET: 90 (100 renewable, 30 storage, 10 distribution)
- FCT: 220 (20 renewable, 150 storage, 5 distribution)
- CAT: 80 (90 renewable, 30 storage, 10 distribution)

Equalling about 20% of total European electricity demand in 2019

<table>
<thead>
<tr>
<th><strong>Point of supply infrastructure</strong></th>
<th>Use of existing facilities</th>
<th>1,400 high power charging points</th>
<th>920 HDV hydrogen filling stations</th>
<th>21,500 km catenary overhead lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYT</td>
<td>0</td>
<td>30</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>BET</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FCT</td>
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<td></td>
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<tr>
<td>CAT</td>
<td></td>
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</tbody>
</table>

**Total Investment (bn €)**

- SYT: 375 (0% for new supply infrastructure)
- BET: 130 (22% for new supply infrastructure)
- FCT: 205 (12% for new supply infrastructure)
- CAT: 135 (32% for new supply infrastructure)

Making zero-emission trucking a reality

The high-demand scenarios cover about 80% of European HDT traffic. SYT with relatively lower energy production investment due 50% import quota.

Source: Strategy& research

September 2020
For each powertrain option, the effect of selected opportunities and threats on the energy cost of long-haul HDTs was investigated.

Long-haul HDT energy prices main opportunities and risks (2030)

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>Assumption</th>
<th>Price at 0.23 €/kWh with area-coverage HPC network</th>
<th>Price at 10.1 €/kg with area-coverage HRS network</th>
<th>Price at 0.39 €/kWh with area-coverage HPC network</th>
<th>Price at 0.19€/kWh, FCT hydrogen price at 3.50 €/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>Enacted CO₂ tax</td>
<td>1.4 €/L with 180 €/tCO₂ currently discussed in scientific community</td>
<td>Low network utilization</td>
<td>Low network utilization</td>
<td>Low network utilization</td>
</tr>
<tr>
<td>Top range</td>
<td>(price raising potential)</td>
<td>1.1 €/L with CO₂ tax at 55 €/tCO₂ as already planned for Germany in 2025</td>
<td>Local production</td>
<td>Medium network utilization</td>
<td>Medium network utilization</td>
</tr>
<tr>
<td>Base case</td>
<td>Low CO₂ tax</td>
<td>0.9 €/L with 0 €/tCO₂ as sensitivity for fossil fuels support</td>
<td>Medium network utilization</td>
<td>Medium network utilization</td>
<td>Medium network utilization</td>
</tr>
<tr>
<td>Bottom range</td>
<td>(price lowering potential)</td>
<td>No CO₂ tax</td>
<td>High network utilization</td>
<td>High network utilization</td>
<td>High network utilization</td>
</tr>
</tbody>
</table>
In a most-likely scenario, energy and infrastructure costs vary quite strongly – fossil diesel remains the cheapest option without CO\textsubscript{2} tax.

Price estimation for end users in 2030 (€ct/km)

**Fuel price for end-user**

Heavy-duty truck (€ct/km)

<table>
<thead>
<tr>
<th></th>
<th>ICE</th>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36</td>
<td>74</td>
<td>33</td>
<td>36</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>31</td>
<td>11</td>
<td>17</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>-5</td>
<td>-14</td>
<td>-7</td>
<td>-10</td>
<td>-24</td>
</tr>
</tbody>
</table>

Fuel consumption per 100km:
- ICE: 33 L
- SYT: 33 L
- BET: 114 kWh
- FCT: 6 kg
- CAT: 106 kWh

Fuel price in standard metric at point-of-sale:
- Base case:
  - ICE: 1.4 €/L
  - SYT: 3.2 €/L
  - BET: 39 ct/kWh
  - FCT: 10.1 €/kg
  - CAT: 95 ct/kWh
- Top range:
  - ICE: 1.1 €/L
  - SYT: 2.3 €/L
  - BET: 29 ct/kWh
  - FCT: 6.8 €/kg
  - CAT: 57 ct/kWh
- Bottom range:
  - ICE: 0.9 €/L
  - SYT: 1.8 €/L
  - BET: 23 ct/kWh
  - FCT: 4.8 €/kg
  - CAT: 34 ct/kWh

*All supply infrastructure investments assumed as surcharge on the fuel price. For CAT, other operation models (e.g. road toll) are not considered. Further, all energy prices are net values without VAT.
Zero-emission trucks can compete with fossil fuel versions when it comes to total cost of ownership.

TCO likely to increase in a zero-emission world

All HDT technologies could have higher TCO in 2030 than today’s ICE. A carbon tax of 55 €/tCO₂ would increase the TCO of diesel trucks by about 10 percent, helping to make alternative powertrains cost-competitive. Synfuels remain the most expensive option – and may bear potential for admixture with fossil diesel.

Zero-emission HDTs can compete on cost

To reach TCO competitiveness, different levers have to be addressed. On the one hand, low powertrain cost and longevity are key to economic competitiveness – such as the increase of battery cycle life for BETs. On the other hand, low energy prices are relevant for long-haul applications – e.g. affordable hydrogen is a key part of making FCTs cost-competitive.

Short-range electrification is attractive

Across all segments, electrification is especially attractive for short-range uses, because the batteries required are smaller. Zero-emission mid-range applications will become cost competitive first for LDTs.
Comparing the relevant TCO elements of alternative powertrains for long-haul HDTs, the effect of selected opportunities and threats was investigated.

### Relevant total-cost-of-ownership (TCO) elements as well as baseline and sensitivities

<table>
<thead>
<tr>
<th>TCO elements</th>
<th>Relevance*</th>
<th>TCO baseline</th>
<th>TCO bottom range</th>
<th>TCO top range (risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>€ Depreciation</td>
<td>Varying vehicle prices</td>
<td>Depreciation based on vehicle prices i.e. 88 k€ for ICE and SYT, 89 k€ for CAT, 145 k€ for FCT and 154 k€ for BET</td>
<td>Increased residual vehicle value due to high stack durability (FCT) and “million-mile battery” (BET)**</td>
<td>(not considered)</td>
</tr>
<tr>
<td>Driver</td>
<td>(not considered)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel (incl. Infrastructure)</td>
<td>Varying energy prices</td>
<td>Fuel cost based on extensive networks i.e. electricity from 0.29 €/kWh (BET) to 0.57 €/kWh (CAT), hydrogen at 6.82 €/kg (FCT) and diesel from 1.08 €/L (ICE) to 2.25 €/L (SYT)</td>
<td>Decreased fuel cost through higher supply network utilization (BET, CAT, FCT) or lower fuel production cost (e.g. import of SynFuel)</td>
<td>Increase fuel cost through lower supply network utilization (BET, CAT, FCT) or local fuel production (SynFuel)</td>
</tr>
<tr>
<td>Insurance</td>
<td>(not considered)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Varying wear efforts</td>
<td>Maintenance based on powertrain technology i.e. 5 k€/a for BET and CAT, 6 k€/a for FCT, 8 k€/a for IC and SYT</td>
<td>(not considered)</td>
<td>(not considered)</td>
</tr>
<tr>
<td>Tax</td>
<td>(not considered)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toll</td>
<td>(not considered)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Relevant for alternative powertrain comparison

** High fuel cell stack durability at 20,000 hrs compared to normal durability at 5,000 hrs; million-mile battery with 3,000 full charging cycles compared to 1,400 charging cycles
By 2030, the TCO of the BET and FCT are already close to the ICE, while other options are far more expensive

TCO for long-haul HDTs in 2030 [€ct/km]

<table>
<thead>
<tr>
<th>TCO 2030 (€ct/km)</th>
<th>ICE</th>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>95</td>
<td>68</td>
<td>65</td>
<td>79</td>
<td></td>
</tr>
</tbody>
</table>

Overall parameters: annual mileage 100 thousand km, holding time 4 years
Toll, insurance, vehicle tax and interest rate not included
* All energy prices net values without VAT

Making zero-emission trucking a reality

TCO components

- Energy & Point-of-Supply Infrastructure
- Maintenance
- Depreciation

September 2020
A CO₂ tax would push alternative powertrain cost competitiveness – ‘million-mile’ battery and low energy prices have a huge impact on TCO

TCO for long-Haul HDTs in 2030 [€ct/km]

<table>
<thead>
<tr>
<th></th>
<th>ICE</th>
<th>SYT</th>
<th>BET</th>
<th>FCT</th>
<th>CAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TCO 2030</strong></td>
<td>57</td>
<td>95</td>
<td>68</td>
<td>65</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>€ct/km</td>
<td>€ct/km</td>
<td>€ct/km</td>
<td>€ct/km</td>
<td>€ct/km</td>
</tr>
<tr>
<td><strong>Fuel price</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top range</td>
<td>1.4 €/L</td>
<td>3.2 €/L</td>
<td>39 ct/kWh</td>
<td>10.1 €/kg</td>
<td>95 ct/kWh</td>
</tr>
<tr>
<td>Base case</td>
<td>1.1 €/L</td>
<td>2.3 €/L</td>
<td>29 ct/kWh</td>
<td>6.8 €/kg</td>
<td>57 ct/kWh</td>
</tr>
<tr>
<td>Bottom range</td>
<td>0.9 €/L</td>
<td>1.8 €/L</td>
<td>23 ct/kWh</td>
<td>4.8 €/kg</td>
<td>34 ct/kWh</td>
</tr>
</tbody>
</table>

**Key takeaway**

- **ICE**
  - Most affordable option, unless there is a significant CO₂ tax (> 50 €/t CO₂)
  - Potential to be used in combination with fossil diesel.

- **SYT**
  - Not an affordable option.
  - Potential to be used in combination with ‘million-mile’ battery required to compete with fossil fueled ICE

- **BET**
  - Low electricity price (<0.25 €/kWh) or ‘million-mile’ battery required to compete with fossil fueled ICE

- **FCT**
  - Low hydrogen price (<5 €/kg) required to compete with fossil fueled ICE

- **CAT**
  - Payback for infrastructure doubtful due to low adoption rates in ramp-up phase
In contrast to long-haul HDTs, electrification is especially attractive for short-range uses in all vehicle segments.

TCO for short- and medium-range uses per truck segment in 2030 [€ct/km]

<table>
<thead>
<tr>
<th>Description</th>
<th>LDT</th>
<th>MDT</th>
<th>HDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily range &lt;200 km</td>
<td>30</td>
<td>63</td>
<td>104</td>
</tr>
<tr>
<td>(~25,000 km per year)</td>
<td>-12%</td>
<td>-13%</td>
<td>-13%</td>
</tr>
<tr>
<td>Example</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery size</td>
<td>60 kWh</td>
<td>150 kWh</td>
<td>250 kWh</td>
</tr>
<tr>
<td>Mid-range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily range 200 km – 400 km</td>
<td>24</td>
<td>51</td>
<td>78</td>
</tr>
<tr>
<td>(~50,000 km per year)</td>
<td>-5%</td>
<td>-4%</td>
<td>+1%</td>
</tr>
<tr>
<td>Example</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery size</td>
<td>150 kWh</td>
<td>300 kWh</td>
<td>500 kWh</td>
</tr>
</tbody>
</table>

Note: This comparison considers depot charging including installation costs for AC charger (LDT) and DC charger (MDT/HDT).

Making zero-emission trucking a reality
Strategy

September 2020
The market share of zero-emission trucks will be significant by 2030 and continue to increase strongly to 2035.

Zero-emission trucks have 32% market share in 2030

After a weak year in 2020 due to the impact of COVID-19, truck sales across all segments are expected to grow by 20 percent by 2030 in Europe. ICE trucks will remain the majority, but zero-emissions trucks will capture around a third of the overall market to comply with fleet emission targets.

LDTs will go electric first

LDTs will lead the change, with the switch to electric vehicles gaining traction from the early 2020s. MDTs and HDTs will be slower, starting with BETs used for short-range journeys.
Four factors will push the attractiveness of zero-emission trucks significantly throughout the next decade

Estimated development of factors over time (2020 – 2030)

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Legislation</strong></td>
<td>• Discussion and introduction of CO₂ standards for heavy-duty trucks</td>
<td>• 56.5g CO₂/tkm as baseline of HDTs for further reductions</td>
<td>• 39.6g CO₂/tkm second reduction goal (~30% from 2019 to 2030)</td>
</tr>
<tr>
<td></td>
<td>• Introduction of first access restrictions</td>
<td>• Access restrictions in place in most European cities</td>
<td>• Widespread prohibition of ICE in European cities</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></td>
<td>• Weak public infrastructure for trucks with alternative powertrains (pilot projects only)</td>
<td>• First publicly available high speed chargers and hydrogen refueling stations for trucks</td>
<td>• Increasing build-up of infrastructure (&gt;100 stations)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No European catenary network</td>
<td>• No European catenary network</td>
</tr>
<tr>
<td><strong>Economics</strong></td>
<td>• ICE most economical for most use-cases</td>
<td>• ICE most economical for most use-cases</td>
<td>• BET and FCT become cost competitive along some HDTs for mid-range (&lt;400 km) applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• BET cost competitive in more segments (MDT) and longer ranges (&lt;300 km)</td>
<td></td>
</tr>
<tr>
<td><strong>Customers and market</strong></td>
<td>• ICE with best usability in focus</td>
<td>• Still ICE with best usability in focus</td>
<td>• Due to high CO₂ taxes, ICE becomes unattractive</td>
</tr>
<tr>
<td></td>
<td>• Most customers of zero-emission trucks are innovative and large companies</td>
<td>• Most customers of zero-emission trucks are early adopters</td>
<td>• Wide customer base of zero-emission trucks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Growing focus on alternative powertrains for trucks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• More zero-emission truck customers</td>
<td></td>
</tr>
</tbody>
</table>
Market share of zero-emission trucks in 2030 across all segments – electrification rate strongest for LDTs and relevant sales in HDT

Truck production forecast in Western Europe (incl. Turkey)

LDT

<table>
<thead>
<tr>
<th>Year</th>
<th>ICE</th>
<th>BET</th>
<th>FCT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2.99</td>
<td>0.0</td>
<td>0.0</td>
<td>2.99</td>
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<tr>
<td>2025</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2030</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
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<tr>
<td>2035</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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</tbody>
</table>

MDT

<table>
<thead>
<tr>
<th>Year</th>
<th>ICE</th>
<th>BET</th>
<th>FCT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
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<tr>
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<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
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<tr>
<td>2030</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>2035</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

HDT

<table>
<thead>
<tr>
<th>Year</th>
<th>ICE</th>
<th>BET</th>
<th>FCT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2025</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2030</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2035</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Zero-emission trucks will make up a third of the European market by the end of this decade.

We can support you in your journey towards a more sustainable future.

**Recommendations**

**Build up an attractive zero-emission portfolio**

OEMs need to **aim for a competitive zero-emission product portfolio** with the focus on **product cost and efficiencies** – from light-duty to heavy-duty trucks. Further, **concentration of development resources on battery and fuel cell trucks** are recommended, which have the most competitive positioning.

**Support infrastructure availability**

OEMs should actively develop and **offer infrastructure options for truck users**. Turnkey depot solutions are mandatory (in cooperation with energy suppliers), while **public infrastructure investments** require governmental backing.

**Prepare the value chain**

Faced with declining revenues from conventional powertrain business, **suppliers should** review their portfolio and **assess their opportunities for taking part in the new zero-emission trucking business**.

**Offer attractive financing**

Due to higher prices, as well as the durability and residual value risks of zero-emission trucks, **OEMs should adjust their financing models** for logistics companies.
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