The potential of e-fuels for heavy duty road transport in the Netherlands

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THE POTENTIAL OF E-FUELS FOR HEAVY DUTY ROAD TRANSPORT IN THE NETHERLANDS

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Samenvatting

In het Klimaatakkoord van Parijs zijn 196 partijen overeengekomen te streven naar een maximale mondiale temperatuurstijging van 1,5°C. Om deze doelstellingen te halen, moet de uitstoot van broeikasgasemissies sterk worden verminderd. Voor de EU is de doelstelling 55% reductie overall voor 2030, ten opzichte van 1990, en tenminste 95% voor 2050. Specifiek voor mobiliteit is de doelstelling 90% reductie voor 2050. Een belangrijke strategie om deze reductie te realiseren is het gebruik van aandrijflijnen en energiedragers die leiden tot een lagere netto uitstoot van broeikasgasemissies.

Doel en opzet van de studie

Het primaire doel van dit project is om de potentie van e-fuels te bepalen voor het gebruik in langeafstandsvrachtvoertuigen (trekker-oplegger combinaties). Dat doen we door een vergelijkende analyse waarin conventionele diesel en verschillende (klimaatneutrale) alternatieven worden meegenomen als opties voor de aandrijving van trekker-opleggers zoals met name toegepast in langeafstandsgoederentransport. De opties die zijn geanalyseerd in deze studie zijn batterij-elektrische vrachtwagens, vrachtwagens met waterstof-brandstofcellen en met waterstof-verbrandingsmotoren, en verschillende uit duurzame energie geproduceerde synthetische brandstoffen (ook wel e-fuels) voor gebruik in verbrandingsmotoren (e-diesel, e-methanol, e-LNG, e-DME). Het gebruik van biobrandstoffen in verbrandingsmotoren wordt enkel kwalitatief behandeld. Al deze energiedragers worden vergeleken op verschillende criteria, te weten emissies (broeikasgas- en luchtverontreinigende emissies), ketenefficiëntie, kosten, veiligheid, toepasbaarheid en 'commercial readiness level' (CRL).

Batterij-elektrische aandrijving zal in een groot deel van het zwaar wegtransport toepasbaar worden

Uit de deze studie kan worden geconcludeerd dat er niet één energiedrager is die het best presteert op alle onderzochte criteria. Met andere woorden, er is geen "silver bullet". Echter, batterij-elektrische voertuigen (BEV) presteren goed op een aantal belangrijke indicatoren zoals kosten, emissies en ketenefficiëntie. De toepasbaarheid of flexibiliteit van deze voertuigen is minder goed dan van andere alternatieven vanwege de beperkte actieradius, maar op termijn naar verwachting toch voldoende voor een groot deel van de vloot. Afhankelijk van de mate waarin logistieke partijen in staat zijn om hun rittenplanning (ritlengte en laadmomenten) goed af te stemmen op de voertuigkarakteristieken, zal de actieradius van BEV's voldoende zijn voor 40% tot 65% van de vloot waarbij enkel 's nachts hoeft te worden geladen. Indien er naast één volledig volgeladen batterij (bijvoorbeeld 's nachts) additioneel maximaal een half uur overdag bijgeladen zou worden (bij 550 kW) zou dit zelfs gelden voor 85% tot 95% van alle trekker-opleggers. Om een aanzienlijk deel van de vrachtwagenvloot te kunnen elektrificeren moeten nog aanzienlijke barrières worden geslecht. Een van deze barrières is de beschikbaarheid van kritieke materialen voor de productie van batterijen en elektrische aandrijvingen. Een andere is dat er voldoende laadinfrastructuur moeten worden gerealiseerd en voldoende capaciteit op het elektriciteitsnetwerk. Aangezien het elektriciteitsnetwerk op veel plekken in Nederland en in andere EU-landen dient te worden verzwaard, mede ten behoeve een door verduurzaming groeiende elektriciteitsvraag van andere sectoren, is het onzeker of de realisatie van laadinfrastructuur voor zware voertuigen het tempo kan bijhouden waarin ontwikkelingen in batterijtechnologie en kosten het toepassingspotentieel vergroten. Daarnaast zijn er ook nog uitdagingen voor logistieke partijen om deze elektrische voertuigen goed in te passen, bijvoorbeeld ten aanzien van parkeergelegenheid tijdens het laden en onderhoud en de beschikbaarheid van onderhoudspersoneel.

Deel van de vloot dat niet één-op-één kan worden vervangen door voertuigen met elektrische aandrijving vereist alternatieve oplossingen

Voor het deel van de vloot zal de één-op-één vervanging door batterij-elektrische voertuigen waarschijnlijk niet mogelijk zijn, bijvoorbeeld vanwege veeleisende inzet (lange afstanden met zware lading), omdat er onvoldoende laadinfrastructuur wordt gerealiseerd of als de ontwikkelingen met betrekking tot prestaties en kosten van de technologie voor BEV's tegenvallen. Daarom is het van belang om ook andere alternatieven te ontwikkelen zoals waterstof en duurzaam geproduceerde koolstofhoudende brandstoffen.

E-fuels: zeer geschikt voor zwaar vervoer en lange afstanden maar pas op langere termijn voldoende beschikbaar en veel elektriciteit nodig voor productie

Voor die laatste optie kijken we in deze studie naar e-fuels, die kunnen worden geproduceerd door duurzame waterstof (gemaakt met zonne- of windenergie) te combineren met CO_2 die wordt afgevangen uit bijvoorbeeld rookgassen of uit de lucht (direct air capture). Voertuigen op e-fuels hebben het voordeel van een grote actieradius en er kan grotendeels gebruik worden gemaakt van bestaande motortechnologie en distributie- en tankinfrastructuur. Aan de andere kant leidt het gebruik van e-fuels wel tot luchtverontreinigende emissies, die overigens steeds verder worden beperkt door steeds strengere wetgeving. Bovendien zal de efficiëntie van de energieketen laag blijven, waardoor er veel meer duurzame elektriciteit, en ruimte om die op te wekken, nodig is dan bij de directe inzet van elektriciteit voor voertuigaandrijving. Dit is vooral op korte en middellange termijn belangrijk zolang duurzame energie schaars is. Op langere termijn hoeft dit geen beperkende factor te zijn, indien een deel van de duurzame energie / brandstoffen geïmporteerd wordt uit regio's met een hogere opbrengst en lagere kosten per eenheid oppervlak voor de opwekking van duurzame elektriciteit. Ook zullen e-fuels naar verwachting pas commercieel beschikbaar zijn vanaf ongeveer 2040. Tussen nu en 2040 zouden biobrandstoffen kunnen dienen als duurzame transitiebrandstof omdat deze net als e-fuels één op één vervanging kunnen zijn van fossiele diesel. De beschikbaarheid van duurzame biomassa voor wegmobiliteit is een potentiële barrière vanwege concurrentie met andere sectoren die biomassa behoeven en met andere modaliteiten zoals de luchtvaart en zeescheepvaart die voor een groot deel afhankelijk zullen zijn van biobrandstoffen en e-fuels. Bovendien dient bij de inzet van biobrandstoffen de grondstof duurzaam te zijn. Dit wordt in steeds betere mate gereguleerd in Europese wetgeving ('Renewable Energy Directive').

Distributie van waterstof is belangrijke bottleneck voor brandstofcellen en verbrandingsmotoren op waterstof

Waterstofvrachtwagens presteren op geen van de hierboven genoemde criteria het beste van de onderzochte energiedragers, maar ook zelden het slechtst. Op termijn zal de TCO naar verwachting vergelijkbaar zijn met die van e-fuel trucks, maar hoger dan die van batterij-elektrische voertuigen. Brandstofcelvrachtwagens stoten geen schadelijke uitlaatgassen uit en presteren op dat punt beter dan vrachtwagens die op e-fuels rijden, maar vergelijkbaar met BEV's. Hun actieradius zal naar verwachting groter zijn dan die van BEV's, maar aanzienlijk kleiner dan die van vrachtwagens die op e-fuels rijden. Bovendien is er nog onvoldoende tankinfrastructuur beschikbaar, alhoewel hier verbetering verwacht wordt, deels onder invloed van Europese regelgeving. De grote uitdaging om die te realiseren is het verkrijgen van waterstof bij het tankstation tegen zo laag mogelijke kosten. Een aansluiting op een pijpleiding kan enkel op locaties waar de pijpleiding al noodzakelijk is voor andere toepassingen zoals industrie. Zelfs waar dit mogelijk is, zijn aanzienlijke kosten gemoeid met de benodigde zuivering van de waterstof voor toepassing in brandstofcellen. Voor het gebruik van waterstof in een verbrandingsmotor zou deze zuivering niet nodig zijn, maar er zal waarschijnlijk maar één kwaliteitsniveau voor waterstof beschikbaar zijn bij tankstations. Indien er voertuigen met brandstofcellen gaan rijden, zal dit waarschijnlijk waterstof zijn van zeer hoge kwaliteit en bijbehorende hogere kosten. Transport middels tankwagens is duur en energie-inefficiënt vanwege de beperkte hoeveelheid waterstof die kan worden vervoerd per tankwagen. Een derde mogelijkheid is lokale productie, maar vereist verzwaring van het elektriciteitsnet en aanzienlijk opslagcapaciteit van waterstof bij het tankstation. Het gebruik van pijpleidingen en lokale productie is in dit rapport echter niet onderzocht. Ten slotte zal voor de waterstofinfrastructuur de synergie met andere vervoerwijzen beperkt zijn aangezien lichte bedrijfsvoertuigen naar verwachting hoofdzakelijk gebruik zullen maken van batterij-elektrische aandrijflijnen. Dit betekent dat de exploitanten van waterstofinfrastructuur grotendeels afhankelijk zullen zijn van een relatief kleine vloot, namelijk enkel een deel van de vrachtwagenvloot.

Naast andere energiedragers, zijn er ook andere oplossingen denkbaar voor een deel van de ritten waarvoor BEV's geen geschikt alternatief zijn. Hierbij kan worden gedacht aan aanpassingen in het logistieke systeem (modal shift, het wisselen van elektrische trekkers of 'near-sourcing') of opladen tijdens het rijden ('in motion charging').

Investeren in kleine markt brengt risico's

Batterij-elektrische aandrijflijnen zullen waarschijnlijk een aanzienlijk deel gaan vormen van de toekomstige, duurzame vloot van trekker-opleggers. Of en hoeveel marktaandeel er zal zijn voor alternatieven zoals waterstof of e-fuels, lijkt sterk af te hangen van de ontwikkeling van BEV's en de beschikbaarheid van laadinfrastructuur. Dit betekent ook dat het risico groter zal zijn voor oplossingen die aanzienlijke investeringen vereisen, die enkel of grotendeels moeten worden terugverdiend via dit nog onbekende marktaandeel. Dit geldt bijvoorbeeld voor waterstof (investeringen vereist in toevoer van waterstof naar tankstations), en niet nader onderzochte opties als in-motion charging (investeringen vereist in bovenleidingen). Voor de andere oplossingen geldt dat de risico's kleiner zijn omdat ze waarschijnlijk ook gebruikt zullen worden in andere toepassingen (productie van e-fuels voor lucht- en scheepvaart) of omdat er in belangrijke delen van de waardeketen geen extra investeringen hoeven te worden gedaan (bepaalde biobrandstoffen en e-fuels kunnen gebruik maken van bestaande distributie-infrastructuur).

Gericht beleid is belangrijk om stappen te kunnen zetten met alternatieven

Om ervoor te zorgen dat alternatieve aandrijftechnieken en energiedragers verder worden ontwikkeld en door de eindgebruikers worden ingezet, moet beleid en wetgeving zodanig worden ingericht dat deze technologieën en producten zonder onnodige of onoverkomelijke hindernissen hun weg naar de markt kunnen vinden. Bovendien moet het beleid zodanig worden opgezet dat de alternatieve technologieën, die vanuit maatschappelijk perspectief het meest wenselijk zijn (op basis van hun bijdrage aan diverse maatschappelijke doelen zoals lage maatschappelijke kosten, betere gezondheid of duurzaamheid), ook aantrekkelijk zijn voor eindgebruikers.

Volgens het huidige beleid en de huidige wetgeving kunnen voertuigen met verbrandingsmotoren die op waterstof of (e-)methanol of (e-)DME rijden amper of geen typegoedkeuring of Euro VI-certificaat krijgen, wat de grootschalige introductie blokkeert en daardoor de verdere technologische ontwikkeling beperkt. Dit probleem zal in de nabije toekomst echter opgelost zijn, omdat er wordt gewerkt aan de voorbereiding van aanpassingen in wetgeving en testprocedures om voertuigen op deze nieuwe brandstoffen te kunnen typekeuren,

Extra of aangepast Europees beleid is nodig om fabrikanten te stimuleren om te investeren in motortechnologie voor toepassing van e-fuels

Omdat de Europese CO_2-wetgeving voor zware wegvoertuigen normen stelt voor de emissies van CO_2 uit de uitlaat, bevordert deze wetgeving vooral de toepassing van technologieën om dieselvoertuigen zuiniger te maken en de inzet van aandrijftechnieken zonder CO_2-uitlaatgasemissies (batterij-elektrisch, brandstofcel-elektrisch en waterstofverbrandingsmotoren). De ontwikkeling en vermarkting van voertuigen die gebruik van duurzame koolstofhoudende (e-)fuels of biobrandstoffen wordt daarentegen door deze wetgeving niet gestimuleerd. Het gebruik van dergelijke energiedragers wordt echter wél bevorderd door de richtlijn hernieuwbare energie (evenals hernieuwbare elektriciteit en waterstof). Dit leidt indirect vanuit de eindgebruikers wel tot een marktvraag richting fabrikanten. Maar omdat de richtlijn hernieuwbare energie door verschillende lidstaten verschillend wordt geïmplementeerd, zal dit tot een gefragmenteerde vraag leiden naar voertuigen op verschillende alternatieve brandstoffen. Extra of aangepast beleid is nodig om vrachtwagenfabrikanten te stimuleren om te investeren in motortechnologie voor toepassing van e-fuels. Het wordt aanbevolen om op EU-niveau opties te verkennen voor nieuwe wetgeving of aanpassing van bestaande beleidsinstrumenten. Het verkennen of voorstellen van opties voor zulke aanpassingen was geen onderdeel van deze studie.

Belangrijk om op te merken is dat -vanuit het perspectief van nieuwe voertuigen- facilitering en stimulering van de inzet van e-brandstoffen en biobrandstoffen alleen van waarde is zolang de toekomstige CO_2-emissienormen voor voertuigen geen volledig verbod op CO_2-uitlaatemissies inhouden. Eisen dat vanaf enig moment alle nieuwe vrachtwagens volledig zero-emission moeten zijn, d.w.z. zonder emissies van CO_2 en luchtverontreinigende stoffen uit de uitlaat, of de Europese CO_2-norm voor HD voertuigen op 0 g/km stellen in de huidige systematiek van deze wetgeving, zou de inzet van verbrandingsmotoren op duurzame koolstofhoudende brandstoffen volledig uitsluiten. Nader onderzoek is nodig om te verkennen hoe de van toepassing zijnde Europese reglementen en verordeningen zodanig kunnen worden aangepast dat alle potentieel benodigde opties toepasbaar blijven voor het halen van de gedeelde ambitie met betrekking tot klimaatneutraal goederenvervoer.

Waar e-fuels (en biobrandstoffen) onmisbaar lijken voor de verduurzaming van andere modaliteiten zoals zeescheepvaart en luchtvaart, lijken deze niet absoluut noodzakelijk voor de decarbonisatie van het zware wegverkeer. Indien e-fuels gebruikt gaan worden, zal dit beperkt blijven tot zware en lange-afstandstoepassingen. Deze markt zal relatief klein blijven en onzeker zijn als gevolg van de toenemende toepasbaarheid van elektrische aandrijving en concurrentie met waterstof (in brandstofcellen en verbrandingsmotoren). Omdat duurzame alternatieven beschikbaar moeten zijn voor alle toepassingen in wegtransport om de lange-termijndoelen voor decarbonisatie van de logistiek te halen, is het echter gerechtvaardigd om verder te investeren in de ontwikkeling en toepassing van trucks op e-fuels, en om beleid te ontwikkelen dat het mogelijk maakt om deze toe te passen in marktsegmenten waar andere duurzame opties niet beschikbaar of toepasbaar zijn. De meest kansrijke e-fuels voor het wegverkeer zijn e-diesel of e-methanol. Gezien de beperkte vraag die er naar verwachting van het wegverkeer zal komen, zal de schaalgrootte en daarmee de prijs en beschikbaarheid van verschillende e-fuels sterk afhangen van de vraag in andere toepassingsgebieden. Welk van deze twee e-fuels de voorkeur zal hebben, zal daar vanaf afhangen.

Summary

In the Paris Climate Agreement 196 parties agreed to strive for a maximum 1.5°C global temperature increase. In order to meet these targets, greenhouse gas emissions must be reduced significantly. For the EU, the target is 55% reduction overall before 2030 and at least 95% reduction before 2050. For mobility specifically the target is 90% reduction by 2050. An important strategy to achieve this reduction is the use of powertrains and energy carriers that lead to net lower greenhouse gas emissions.

Objective and scope of this study
The primary goal of this project is to determine the potential of e-fuels for use in long-haul trucks, specifically tractor trailer combinations. This is done through a comparative analysis taking into account conventional diesel and a range of (climate neutral) options for alternative drivetrains and energy carriers. Included in the scope of this project are battery electric trucks, hydrogen fuel cell trucks, hydrogen combustion engine trucks and various types of e-fuels to be used in combustion engines (e-diesel, e-methanol, e-LNG, e-DME). Biofuels in combustion engines are only considered qualitatively. All included options are compared on various criteria, such as emissions (greenhouse gases and pollutants), energy chain efficiency, cost, safety, applicability and commercial readiness level (CRL).

Battery-electric propulsion will become applicable in a large share of all heavy road freight transport
This study shows that there is no single energy carrier that performs best on all the criteria on which they are assessed. In other words, there is no "silver bullet". However, battery-electric vehicles (BEVs) perform well on various important indicators, such as costs, emissions, and chain efficiency. The applicability or flexibility of BEVs is less than that of other alternatives due to their limited range, but in the coming years it is expected to be sufficient for a substantial part of the fleet. Depending on the extent to which logistic companies are able adjust their planning (trip-length and recharging) to the characteristics of BEVs, the range of such vehicles will be sufficient for 40% to 65% of the fleet with only overnight charging. One fully charged battery (e.g., overnight charging) plus half an hour additional recharging during the day (at 550 kW) would increase this share to 85% to 95% of all tractor-trailers. In order for a substantial part of the truck fleet to become electric, considerable barriers still have to be overcome. One of such barriers is the availability of certain critical materials required for the production of batteries. Another example is that sufficient recharging infrastructure will have to be realised and sufficient capacity provided on the electricity grid at locations where and times when this is required. Since the electricity network needs to be strengthened in many places in the Netherlands and other European countries, also due to demand in other sectors, it is uncertain whether the realisation of charging infrastructure for heavy duty vehicles can match the speed at which developments in battery technology increase the application potential of this technology. Moreover, additional challenges for logistics companies to fit these BEVs in properly are, for example, parking facilities during charging and maintenance and the availability of maintenance personnel.

Alternative solutions required for part of the fleet that cannot be replaced one-on-one with electric vehicles
Battery-electric trucks will probably not be able to replace all vehicles in the fleet, for example due to demanding operations (long distances with heavy loads), because insufficient charging infrastructure is realised or if the technological development of BEVs lags behind. Therefore, it is very important that also other alternatives are being developed, such as hydrogen and sustainably produced carbon-based fuels.

E-fuels are suitable for heavy transport applications and long distances, but will only be sufficiently available in the longer term

For the latter option this study looks at e-fuels which can be produced by combining renewable hydrogen (made with solar or wind energy) with CO2 that is captured from flue gases or from the atmosphere (direct air capture). Vehicles on e-fuels have the advantage of a long range and the possibility to use existing engine technology and refuelling infrastructure. On the other hand, the use of such e-fuels leads to tailpipe emissions, which however will reduce to lower levels due to ever more stringent legislation. In addition, the efficiency of the energy chain will remain low even in the further future, requiring a larger amount of energy and space to generate electricity than the direct application of renewable electricity in for vehicle propulsion. This is especially important in the short to medium term, as long as renewable energy is scarce. In the longer term this need not be a limiting factor, when part of the renewable energy / fuels is imported from regions with a higher yield and lower costs per unit of space for generating renewable electricity. Also, e-fuels are not expected to be commercially available until around 2040. Between now and 2040, biofuels could serve as a sustainable transition fuel because, like e-fuels, these are drop-in fuels. The possibility to use biofuels in mobility strongly depends on their availability, especially given competition with other modalities such as aviation and maritime shipping, which will be largely dependent on biofuels and e-fuels. Moreover, when considering the use of biofuels, it is very important that the sustainability of the feedstock is guaranteed. European regulation on this matter is becoming more and more stringent ('Renewable Energy Directive').

Distribution of hydrogen is an important bottleneck for fuel cells and hydrogen combustion engines

Hydrogen trucks do not have the highest score for any of the indicators assessed, but also hardly ever the lowest. In time, the TCO is expected to equal that of e-fuel trucks, but will remain higher than that of battery-electric vehicles. Fuel cell trucks emit no harmful tailpipe emissions and on that aspect outperform e-fuel trucks, but are comparable to BEVs. Their range is expected to be greater than that of BEVs, but considerably smaller than that of e-fuel trucks. Moreover, there is not yet enough refuelling infrastructure available, although this is expected to improve, partly driven by European regulations. The big challenge is to get hydrogen to the refuelling station at reasonable costs. A pipeline connection is only possible at locations where the pipeline is already necessary for other applications such as industry. Even where this is possible, necessary purification of the hydrogen for use in fuel cells is costly. Such purification would not be required for the use of hydrogen in combustion engines. But if fuel cell vehicles will be employed there will likely be only one hydrogen quality be available, which is variety with the higher purity and associated higher costs. Transport by tube trailers is expensive due to the limited amount of hydrogen that can be transported per trip. A third possibility is local production, but this requires reinforcement of the electricity grid and considerable hydrogen storage capacity at the refuelling station. However, the use of pipelines or local production was not assessed in this study. Finally, for hydrogen infrastructure, synergies with other transport modes will be limited as light duty vehicles are expected to use mainly battery-electric powertrains. This means that operators of hydrogen infrastructure will be largely dependent on a part of the truck fleet only.

Besides the use of other alternative energy carriers, other solutions are available to decarbonise the share of the fleet for which BEVs are not a suitable alternative. Possible solutions are adjustments to the logistical system (modal shift, changing electric tractors during a long trip or 'near-sourcing') or in-motion charging.

Investing in a small market brings significant risks

Battery-electric powertrains are likely to take a significant market share of the tractor-trailer fleet. The potential market share for other solutions, such as the use of hydrogen or e-fuels, will depend strongly on the development of BEVs and the availability of charging infrastructure. This also means that the risk will be higher for solutions that require substantial investments that have to be earned back largely or solely through this unknown and uncertain share of the fleet. This applies for example to hydrogen (investments required in the supply of hydrogen to refuelling stations) or in-motion charging (investments required in overhead wires). For the other solutions, the risks are lower because they are likely to be used in other applications (e-fuels for aviation and shipping) or because no additional investment is needed in important parts of the value chain (some biofuels and e-fuels can use existing infrastructure).

Specific policy is paramount for accelerating the uptake of alternatives

In order for alternative drivetrain types and energy carriers to be developed and taken up by end users, policies and legislations should be designed in such a way that these technologies and products can find their way to the market without unnecessary or impassable hurdles. Moreover, policies should be designed in such a way that the alternative technologies that are favorable from a societal perspective (based on their contribution to various societal objectives such as low societal cost, improved health or increased sustainability) are also attractive for end users.

Current policies and legislation does not allow combustion engine vehicles running on hydrogen, (e-) methanol or (e-)DME to be type approved or Euro VI certified. This blocks their uptake and therefore limits further technological development. However, as these are relatively new technologies, the process for catering for these options has already started and it is expected that in the near future this will no longer be a problem.

Additional or adapted EU policies are necessary to stimulate manufacturers to invest in engine technology for application of e-fuels

As European CO_2-legislation for heavy duty road vehicles sets standards for the tailpipe emissions of CO_2, this legislation promotes the application of technologies to reduce the fuel consumption of diesel vehicles as well as the application of propulsion technologies without tailpipe CO_2 emissions (battery-electric, fuel cell electric and hydrogen combustion engines). The development and marketing of vehicles running on renewable, carbon-based (e-)fuels or biofuels is not incentivized by this legislation. However, the use of such fuels is promoted, or even mandated, by the Renewable Energy Directive (as are renewable electricity and hydrogen). Indirectly this does create a market demand for alternatively fueled vehicles. But as the directive is implemented in different ways by different Member States, different options may be preferred in different countries leading to a fragmented demand for vehicles on alternative fuels. Additional or amended policies are needed to stimulate truck manufacturers to invest in engine technology for application of e-fuels. It is recommended to explore options at the EU-level for new legislation or adaptation of existing policy instruments. Exploring or proposing options for such amendments was not part of this study.

Important to note is that, from the perspective of new vehicles, crediting of e-fuels and biofuels is only valuable as long as future HDV CO_2 emission targets are not completely prohibiting tailpipe CO_2 emissions. With the current design of the regulation, demanding that from some point onwards all new HDVs should be zero emission, i.e. without emissions of CO2 and air pollutants from the exhaust, or setting the European CO_2 standard for HD vehicles at 0 g/km in the current legislative system would completely rule out the deployment of internal combustion engines on sustainable carbon-based fuels. Further research is required to explore how the applicable European regulations and directives can be adapted in such a way that all potentially viable options remain applicable for achieving the shared ambition regarding climate neutral freight transport.

Whereas e-fuels (and biofuels) seem indispensable for decarbonizing other transport modes such as maritime shipping and aviation they do not seem necessary for the decarbonisation of heavy road traffic as more alternatives are available. If e-fuels will be used, this will be limited to heavy and long-distance applications. This market will be relatively small and remains uncertain due to the increasing potential of *electric trucks and competition with hydrogen (in fuel cells or combustion engines). Nevertheless, as sustainable alternatives are needed for all road freight applications to achieve long term targets for full decarbonization of logistics, it seems justified to invest further in the development and application of trucks running on e-fuels and to implement policies that allow this technology to be implemented in those market segments where other sustainable options are not available or suitable. The most promising e-fuels for road transport are e-diesel or e-methanol. Given the limited demand expected from road traffic, the production scale and hence the price and availability of these e-fuels will depend heavily on demand in other application areas. Which of these two e-fuels will be favoured in the end may also depend on developments in other sectors.*

CONTENTS

Abbreviations

BEV	Battery Electric Vehicle
CRL	Commercial Readiness Level
DME	Dimethyl-ether
FCEV	Fuel Cell Electric Vehicle
H_2	Hydrogen
HDV	Heavy Duty Vehicle
ICE(V)	Internal Combustion Engine (Vehicle)
LH	Long Haul
LHV	Lower Heating Value
LNG	Liquified Natural Gas
MCA	Multi-Criteria Analysis
Methanol	Methanol
NH_3	Ammonia
NO_x	Nitrogen Oxides
PM	Particulate Matter
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZE	Zero-Emission

-01-

Introduction

1.1 Background

The Paris Agreement was adopted by 196 Parties at 2015 COP21 in Paris and entered into force in 2016. It is a legally binding international treaty on climate change agreeing to limit global warming to well below 2°C and strive for 1.5°C compared to pre-industrial levels. Meeting these goals requires a steep reduction of GHG emissions to achieve a net global climate neutrality by 2050.

In the EU mobility is the only sector of which GHG emissions are currently higher than 1990 levels. Growth of mobility demand has been dominant over the implementation of GHG emission reducing measures, such as vehicle energy efficiency improvements and modal shift. A proportional contribution to meeting climate goals is therefore challenging for the mobility sector.

Potential ways to realise the net reduction of GHG emissions from transport are:

- the reduction of mobility demand (less transport of people and goods),
- a (partial) shift to transport modes with lower GHG emissions or
- the use of drivetrains and energy carriers that result in lower net GHG emissions: electricity, hydrogen, certain biofuels, or renewable e-fuels.

In the Power2Fuels study (TNO, 2020a), sponsored by Voltachem and Smartport, TNO in collaboration with many stakeholders conducted an initial exploration and comparative analysis of options for the deployment of e-fuels in heavy road transport, shipping, and aviation as a measure to make these modalities more sustainable. For trucks, the following options were assessed and compared to the reference fuel diesel: hydrogen, e-methanol, e-diesel, e-LNG, and e-ammonia. It was concluded that e-methanol, e-diesel, and e-LNG are suitable for all truck applications. Hydrogen was concluded to be particularly interesting for shorter distances and in scenarios with high costs for renewable electricity or the CO_2 required for producing e-fuels. E-ammonia was considered not suitable for trucks due to safety concerns. The current project builds on the earlier Power-to-Fuels project and specifically zooms in on e-fuel applications for long-distance heavy duty road transport.

Hydrogen	For short distances, in case of high electricity and CO_2 costs		
E-methanol	Feasible		
E-diesel			
E-LNG			
E-ammonia	Unsafe	In case of high CO_2 cost	
E-kerosene			Only feasible option

Figure 1: Viable options for e-fuels for various modalities (TNO, 2020).

In contrast to the Power2Fuels study, battery electric drivetrains will also be considered in this study. The complete list of energy carriers and drivetrains taken into account are shown in section 1.4.

1.2 Objective

The primary goal of this project is to create insight in the suitability of different e-fuels as options for climate neutral heavy road transport. To this end a comparative analysis is made taking into account conventional diesel as well several other (climate neutral) alternative drivetrains and energy carriers such as battery electric drivetrains. We do this by means of scientific fact-finding and analysis as well as knowledge exchange and joint evaluation of results with stakeholders from various sectors[1] relevant for the production and use of transport fuels, and by exploring 'possible transition paths for the use of e-fuels in heavy road transport.

1.3 Approach

Technical analysis alone is not enough to determine which energy carriers could play a key role in the transition towards sustainable road transport. It also requires knowledge from other disciplines and insights from different domains as well as different perspectives. Similarly the transition towards the large-scale use of alternative energy carriers and drivetrains requires efforts from many involved parties. For instance, the roll-out of e-fuels in heavy road transport involves major investments in, among other things, new production facilities, distribution routes, storage, infrastructure, and vehicles. It is therefore also difficult to give a simple answer to the apparently simple question of "When can I buy the first truck on e-fuels?".

In this project an assessment framework has been developed, in which different sustainability options can be compared. The previous 'Power to Fuels' project and the Multi-Criteria Analysis (MCA) developed therein form a good basis for this, but require extension to include battery electric trucks, hydrogen combustion engines (H_2-ICE) and e-dimethyl ether (e-DME).

For each of the parties in the supply chain a profitable business case is an important criterion when deciding for a switch to e-fuels. The attractiveness to end users will depend to a large extent on the availability of e-fuels and prices at the pump. These again depend on the costs for production, distribution and storage, which vary for different scales and distribution methods (central/large scale vs. decentralized/small-scale or in between). These factors are therefore taken into account in determining the TCO for the various drivetrains and energy carriers. It will also take into account different scenarios over time (2020 / 2030 / 2040), with varying assumptions about the production scale and the development of component costs and energy prices.

Timing plays an important role in the transition to the use of e-fuels in heavy road transport. The steps for upscaling must be geared to the availability of e-fuels (production volumes), suitable vehicles (trucks) and a comprehensive network for refueling. Here choices need to be made to solve possible chicken-and-egg situations, while avoiding unprofitable business cases (e.g., due to under-utilisation of refuelling infrastructure). To provide insights in potential timing issues, the commercial readiness level of fuel production, vehicle production and infrastructure roll-out is also assessed in this project.

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1 SmartPort, DAF, Overbeek B.V. Van Berkel Logistics, DHL, Shell, VOPAK

1.4 Scope

The scope of this study is the application of e-fuels in trucks deployed for long haul transport. Since tractor-trailers are by far the most used vehicle type for such applications, the quantitative assessments focus on this vehicle type.

To assess the suitability and attractiveness of e-fuels to decarbonise heavy-duty (HD) long haul transport, this study compares alternative energy carrier solutions based on the following criteria:
- Energy efficiency and environmental impact
  - Production efficiency (WTT)
  - Emissions (WTW)
  - Drivetrain efficiency (TTW)
  - Environmental impact (WTW) of long-haul traffic in the Netherlands
- Total mobility chain cost
  - Fuel production cost
  - Distribution cost
  - Infrastructure cost
  - Vehicle cost
- Safety
- Applicability/usability
  - Case-study based on logistical data
  - Case-study on national / European scale
  - Qualitative considerations from an end-user perspective
- Commercial readiness level
- Legislation

Besides these, there are other criteria that are also relevant, e.g., circularity of the components and materials used the vehicle. Such criteria have not been considered in this assessment.

Each of the included criteria are important to various parties in the value chain, and thus from different points of view. In this study the criteria are explored from the perspectives of fuel production companies, original equipment manufacturers (OEMs), and end-users (logistics companies) as well as from a broader societal perspective. Safety is relevant and important in every part of the chain. Nevertheless, safety implications vary significantly from different points of view. Well-to-Tank energy efficiency is important from a societal and systemwide perspective, however it also influences the Total Cost of Ownership (TCO) on multiple levels. Applicability and cost are crucial factors from an end-user perspective.

Three different drivetrain technologies and six different energy carriers are selected and analysed in this project:
- Internal combustion engine vehicle (ICEV)
  - e-diesel
  - e-methanol
  - e-dimethyl-ether (DME)
  - e-LNG
  - hydrogen
- Battery-electric vehicle (BEV)
  - electricity
- Fuel-cell electric vehicle (FCEV)
  - hydrogen

Within the context of reducing the climate impacts of long-haul heavy duty road transport sustainable biofuels (and blends of biofuels with fossil fuels or even e-fuels) are another important option. These, however, are outside the scope of this project and are therefore not taken into account in the analysis. However, some qualitative remarks with respect to biofuels are included in the text when relevant.

Analysis of the deployment of trucks is based on the Dutch situation, due to the availability of data. Since the deployment of trucks differs per country, conclusions regarding

1.5 Report structure

In Chapter 2 the scope and context regarding heavy duty road transport in the Netherlands is defined. Chapter 3 provides an overview of the assessed energy carriers in this study. Results of the comparative analysis on energy efficiency, environmental and social criteria are presented in Chapter 4. The cost aspects concerning the value chain of the considered fuels is presented in Chapter 5. A safety analysis based on risk and impact assessment in case of calamities is discussed in Chapter 6. Chapters 7 and 8 deal with more qualitative criteria such as applicability, flexibility, and commercial readiness. Chapter 9 addresses relevant European legislation and standards which can affect the market introduction and deployment of various drivetrain and fuel options. Finally in Chapter 10 a discussion on the results is presented.

-02-

Heavy duty road transport in the Netherlands

In this chapter the definition of heavy-duty road transport in the Netherlands, as used in this study, is described. The characteristics of this sector are further defined by means of average daily operational data of a logistical service provider.

2.1 Registrations & kilometres

About 170,000 trucks were registered in The Netherlands in 2019 (CBS). Approximately 43% of these were articulated and rigid trucks. 57% were tractor-trailers, as can be seen in Figure 2.

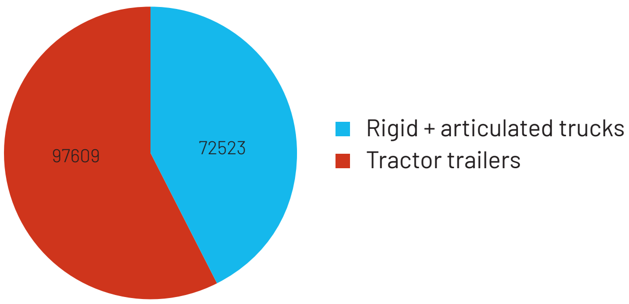

Figure 2: Registered trucks and tractor-trailers in the Netherlands in 2019 (CBS).

Together these trucks drove approximately 9.4 billion kilometres. This results in an average of 55,200 kilometres per vehicle per year. The average annual mileage per tractor-trailer is approximately 70,800 kilometres. At 260 working days per year this would result in an average daily mileage of 270 kilometres.

Table 1: Registered trucks and tractor-trailers in the Netherlands in 2019 (CBS).

Year: 2019	**# Vehicles**	**# mln kilometres**	**# Annual mileage ` per vehicle**
Rigid trucks	72,523	2,479	34,184
Tractor-trailers	97,609	6,913	70,824
Total	**170,132**	**9,392**	**55,205**

Long-haul transportation is done by tractor-trailers, but tractor-trailers are also deployed for other types of use, e.g., regional distribution. The annual mileage of long-haul trucks will typically be larger than that of trucks used for regional distribution. Whether a truck is being deployed for long-haul or regional distribution purposes cannot be derived from its annual mileage. Certain intensively used regional delivery tractor-trailers may drive more kilometres than long haul tractor-trailers that are not used on a daily basis.

2.2 Environmental impact in the Netherlands

According to CBS, trucks and tractor-trailers were responsible for the emission of approximately 5.8 Mton CO_2 in the Netherlands in 2018. Moreover, they emitted approximately 23.7 kton of NO_x and 0.29 kton of PM10 (from tailpipe). With the TNO Decamod model it was determined that long-haul transport by tractor-trailer is responsible for 2.9 Mton of CO_2 emission in the Netherlands (TNO, 2021). The amount of energy used is roughly equal to 39 Peta Joule (PJ) of diesel (TTW).

2.3 Use of tractor-trailers in the Netherlands

Figure 3 shows the cumulative share of vehicles driving a certain average daily distance. The annual average daily mileage is derived from the annual mileage of individual tractor-trailers in the Dutch vehicle fleet, assuming 260 driving days per year.

The figure shows that approximately 24% of tractor-trailers drives less than 200 km per day on average. 92% of tractor-trailers drives an average daily distance of less than 500 km. It can therefore be concluded that the share of tractor-trailers that are used for long haul transport daily is limited. However, it could be that vehicles are used for long haul transport on some days and for shorter trips or not at all on other days. This would limiting their average daily mileage to levels equal to vehicles used for regional transport that are deployed on a daily basis.

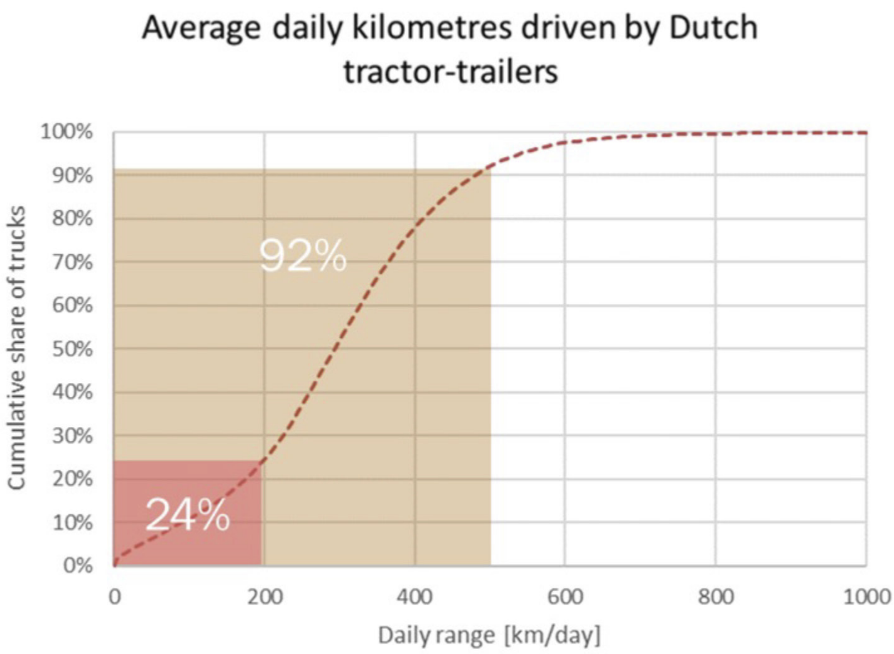

Figure 3: Cumulative distribution of average daily distance driven by tractor-trailers in the Netherlands (CBS, 2014).

2.4 Long-haul container transport – a case study

In this section an analysis is presented on daily driving distances for logistical service provider Overbeek BV. The operational characteristic of their vehicles gives relevant insights for assessing the potential role for various energy carriers in this sector.

2.4.1 Added value of the use-case

Compared to the data available for a large share of the tractor-trailer fleet in the Netherlands (in the previous paragraph), the data provided by Overbeek BV is more detailed. Whereas the overview of tractor-trailer deployment in the Netherlands as provided in the previous paragraph only includes annual average daily mileages per vehicle, the data provided by Overbeek BV allows more detailed analyses, e.g., the variation in daily mileages on a day-to-day basis. Such variation is an indication for the required flexibility for the deployment of the trucks: a larger variation of the daily mileage, means that more flexibility is required. If trucks were to be replaced one on one by vehicles with alternative drivetrains or energy carriers, the range of the truck should be sufficient to cover the day with the highest mileage or at least a large share.

2.4.1 Deployment characteristics

In Figure 4, heatmaps of trip origins and destinations in Europe and in the Netherland are visualized. From this first initial visualization it can be observed that the largest share of trips is concentrated in and just around the Netherlands, especially around Rotterdam and Antwerp. This is a first indication that many of the trips are driven over relatively short distances.

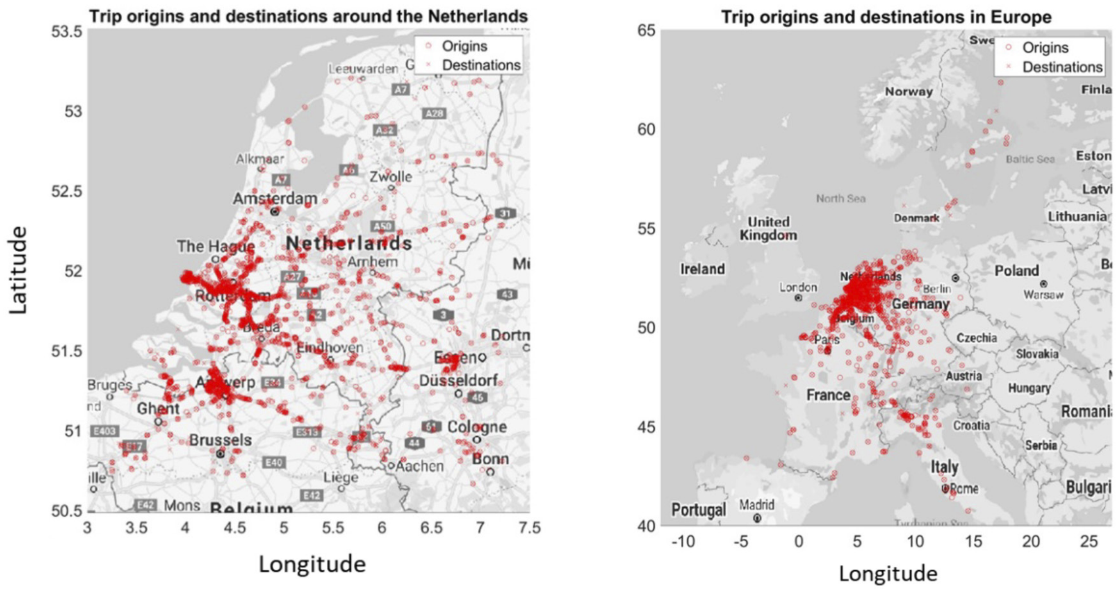

Figure 4: Heatmaps of trip origin and destination in and around the Netherlands and in the rest of Europe.

The average daily driven distance per vehicle over a five-month period is plotted. From this analysis it can be concluded that for logistical service provider assessed here approximately 17% of daily driven distances are below 200 km and 99% of vehicles drive less than 500 kms per day.

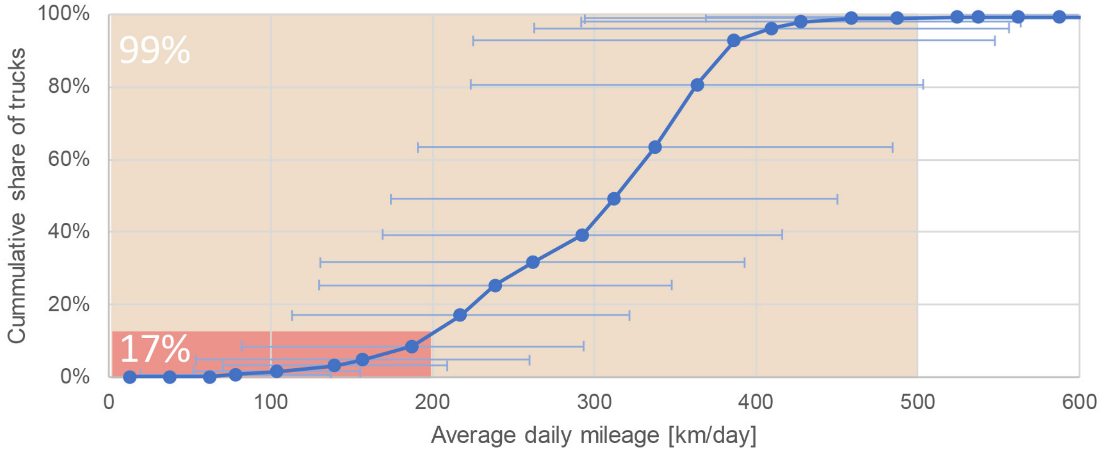

Figure 5: Distribution of average daily distance driven (and standard deviation) by individual trucks of Overbeek BV.

This figure also shows the deviation between days, not considering the days on which they are not being used. For instance, trucks that drive an average of 300 km/day, have a standard deviation of 130 km/day. This means that about two thirds of the days they drive between 170 km/day and 430 km/day. About 95% of the days these trucks drive between 40 km/day and 560 km/day. This shows that trucks are being deployed quite differently on different days. Currently logistics companies have no real incentive to limit the flexibility of truck deployment since the diesel trucks all have a large range. In case the range of trucks is more limited (e.g. in case of battery electric trucks) such companies could reduce the flexibility of deployment. To what extent this can be realised is not investigates in this project.

-03-

Overview of assessed energy carriers

3.1 Alternative energy carriers overview

The focus of this study is on e-fuels (e-methanol, e-diesel and e-DME), hydrogen and electricity. As these are assessed as options for reducing the CO_2 emissions from road freight in the longer term (up to 2050), the electricity required for producing the e-fuels and H_2 is assumed to be produced from renewable sources (i.e., wind and solar). Figure 6 shows a schematic overview of the production processes for renewable e-fuels.

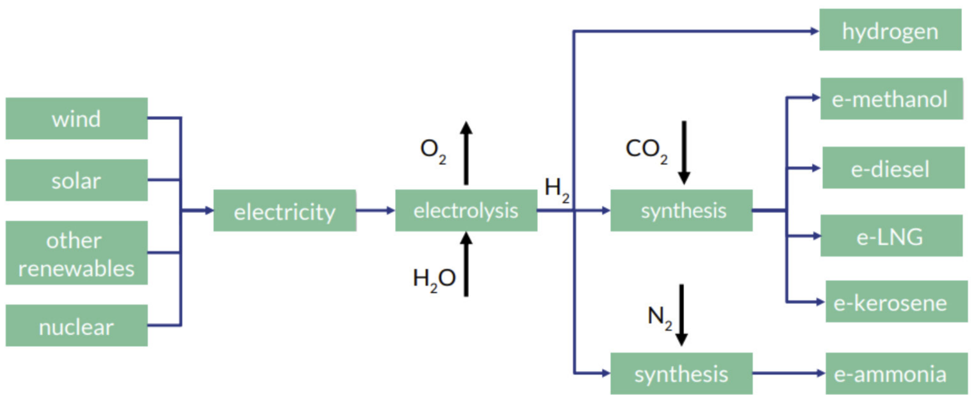

Figure 6: Production routes of the various energy carriers (TNO, 2020a).

3.2 Energy carriers and production chain

The value chain to produce energy carriers (WTT) can be segmented in three main elements:

- Production & conditioning of energy carriers at source (not including the production of facilities or equipment, e.g., refineries, PV panels, wind turbines);
- Transportation & transformation at source and near market;
- Distribution & conditioning.

A schematic overview of these chain elements and the two pathways is displayed in the figure below. In the first step, the energy carrier is produced from resources (e.g., electricity is produced from wind by use of a wind turbine). In the second step the energy carrier needs to be transported from the production source to or near the market. In some cases, a transformation step (e.g., transforming natural gas into LNG by cryogenic liquefaction) or storage is required. The distribution step describes the last step of the WTT pathway from the processing or storage facility to the refuelling or recharging station.

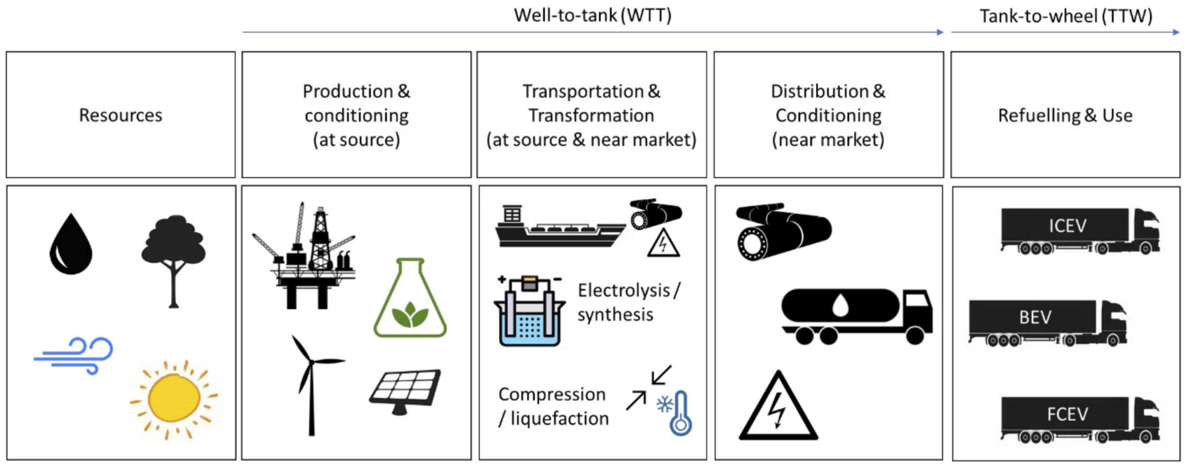

Figure 7: Various steps in the Well-to-Wheel (= Well-to-Tank + Tank-to-Wheel) chain for energy carriers.

From this schematic overview it becomes evident that there exist a vast number of value chains that can be studied since, in principle, an energy carrier can be produced and distributed via different conversion and transportation routes.

3.3 Selected conversion routes

In this study for every assessed energy carrier a specific 'route' is selected from (TNO, 2021c). In case information was not available, e.g., fossil diesel production, DME synthesis and distribution and dispensing of fuel, it was obtained from the WTT report from JRC (JRC, 2020). Table 2 provides an overview of the selected routes for this study and the corresponding JRC pathway codes.

Table 2: Selected energy carriers with corresponding JRC 2020 codes (grey = fossil, green = electricity, blue = hydrogen, orange = e-fuels).

Energy carrier	**Pathway**	**Information source**
Diesel	Fossil diesel – Typical EU supply	(JRC, 2020): route COD1
Electricity - renewable	Wind turbines	(JRC, 2020): route WDEL
Hydrogen - renewable	Wind turbines (EU offshore) + central electrolyser, compression (840 bar). Truck distribution 200 km with electric trucks.	• H_2 production: (TNO, 2021c) • Distribution (JRC, 2020): route GPCH3b* • Rest (JRC, 2020): route WDEL1/CH2
e-diesel	Import of e-diesel from Canada, Electricity from wind turbines, CO_2 from Direct Air Capture. Truck distribution 200 km with electric trucks.	• Distribution & dispensing: (JRC, 2020): route RESD2c • Rest: (TNO, 2021c)
e-methanol	Import of e-methanol from Canada, Electricity from wind turbines, CO_2 from Direct Air Capture. Truck distribution 200 km with electric trucks.	• Distribution & dispensing: (JRC, 2020): route REME1a • Rest: (TNO, 2021c)
e-DME	Import of e-DME from Canada, Electricity from wind turbines, CO_2 from Direct Air Capture. Truck distribution 200 km with electric trucks.	• Distribution & dispensing and DME synthesis: (JRC, 2020): route REDE1a • Rest: (TNO, 2021c)

Energy carrier	Pathway	Information source
e-LNG	Import of e-LNG from Canada, Electricity from wind turbines, CO_2 from Direct Air Capture. Truck distribution 200 km with electric trucks.	• Distribution & dispensing: (JRC, 2020): route GRLG1* • Rest: (TNO, 2021)

* Corrected for distribution distance.

-04-

Energy efficiency and environmental impact

The production processes and distribution systems of the various energy carriers are different. As a result, the energy required to get the energy carriers to the end-user varies. Electric trucks require a battery and electric motor, while hydrogen trucks require a fuel cell or combustion engine. Trucks driving on e-fuels (in this study) use an internal combustion engine (ICE). These distinct types of drive-trains typically have different energy efficiencies. Combining the Well-to-Tank (WTT) efficiency of the production chain and the vehicle's Tank-to-Wheel (TTW) energy consumption yields the total Well-to-Wheel (WTW) energy consumption of the energy chain associated with using a specific energy carrier. In this chapter the energy efficiency as well as environmental effects are analysed.

4.1 Energy efficiency

4.1.1 Well-to-Tank energy consumption

Since the production, transformation, and transportation phases all require energy, the energy input into the process is larger than the final energy produced. This can be expressed in mega joules (MJ) of energy used per mega joule (MJ) of 'fuel' produced. The energy associated with production of the production sites, such as electrolysers and wind turbines and oil refineries, as well as distribution infrastructure are not included in this comparison.

Figure 8 shows the specific energy consumption in $MJ_{energy\text{-}expended}/MJ_{fuel}$ for the various energy carriers assessed in this study. For more detailed values, the reader is referred to Appendix A. The following conclusions can be drawn from Figure 8:

- It is noticeable that the WTT energy loss of fossil diesel is limited, 0.3 MJ of energy is used to produce and distribute 1 MJ of diesel.
- It can be seen that for the sustainable options, the production of green electricity is by far the most energy efficient process. This excludes any charging losses as these are accounted for in the tank-to-wheel energy usage (4.1.2).
- The selected hydrogen route in this study uses green electricity for the electrolysis process. During electrolysis, energy is used and the amount of output energy in the form of hydrogen is lower than the electric energy put into the system. As a result of the inherently low volumetric energy density of hydrogen (even under pressure) the energy required to distribute the fuel is significantly higher than with other assessed energy carriers. In case the hydrogen is distributed with diesel trucks instead of electric trucks, the additional energy required per unit of energy would be even higher, i.e., 2.5 MJ/MJ instead of 1.4 MJ/MJ. On the other hand, if the distribution is (partly) done via pipeline instead of truck transport, the required energy would be lower, although this is only cost effective at sufficiently high throughput (see section 5.2.2.3). Also local hydrogen at the filling station might be more efficient, depending on the efficiency of small scale electrolysers. These alternative options, however, were not included in this study as truck distribution is expected to be the main way of transportation for the

next decade in the Netherlands.

- The production of e-fuels requires more energy than the production of green hydrogen or green electricity. This is due to additional conversion steps (hydrogen is required to produce liquid e-fuels) and other production processes.

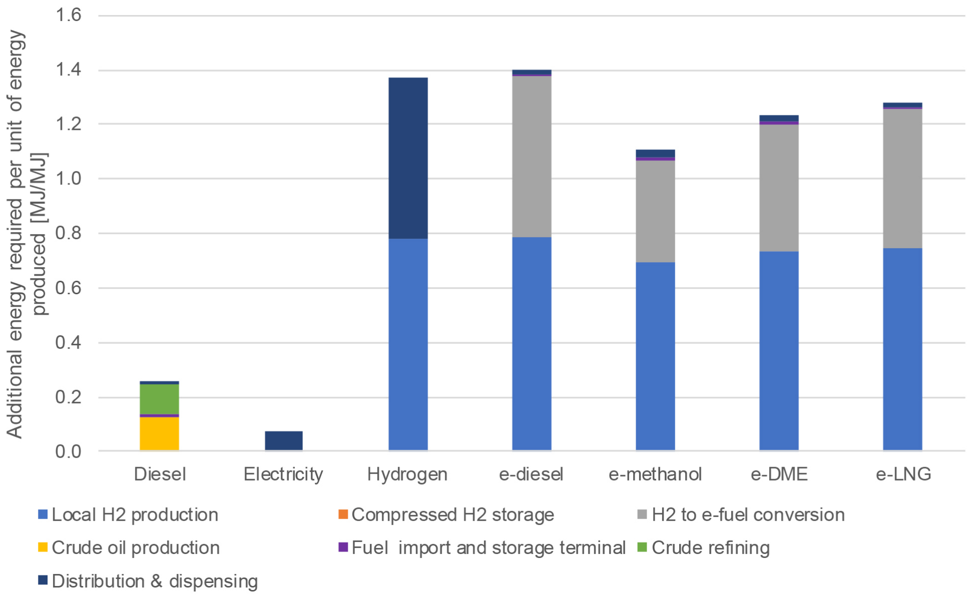

Figure 8: Well-to-tank energy requirement to produce the various energy carriers, (excluding charging losses)[2]. Energy required for direct air capture is included in "H_2 to e-fuel conversion"

4.1.2 Tank-to-Wheel energy consumption

As mentioned in Section 1.4, the focus in this study is on long-haul tractor-trailer combinations. Table 3 provides an overview of the considered powertrain technologies in this study.

Table 3: Overview of driveline configurations and reference vehicles, CI is compression ignition and SI is spark ignition.

Drivetrain	Energy carrier	Energy conversion principle	On-board energy storage
ICE	(e-)diesel	Compression ignition (CI) engine	Ambient conditions
	hydrogen	Spark ignition (SI)[3] engine	Compressed (700 bar)
	(e-)methanol	Direct injection (DI) – dual-fuel engine	Ambient conditions
	(e-)DME	Compression ignition (CI) engine	Compressed (6 bar)
BEV	Electricity	electric motor	Battery pack
FCEV	Hydrogen	fuel cell + electric motor	Compressed (700 bar)

2 "Distribution & dispensing", "crude oil production" and "crude refining" based on (JRC, 2020). "Distribution & dispensing" corrected for 200 km distance and electric trucks instead of diesel trucks. Efficiency ratio between electric and diesel trucks based on 4.1.2. All others based on (TNO, 2021c)

3 SI and CI are both possible. For CI different concepts (mono or dual fuel) are proposed in literature.

Since different technologies have different driveline efficiencies it is important to specify the used values. The assumptions for this study are based on simulations using the ADVANCE model (TNO, 2002) reported in a recent TNO study on the potential uptake of zero-emission trucks for Transport and Environment (TNO, 2022). In that study, the energy consumption of long-haul tractor trailers is modelled for the years 2020, 2030 and 2040 using VECTO drive cycles amongst which also the long haul cycle.

While e-diesel and e-DME engines are expected to have a similar efficiency as the normal diesel powertrains (TNO, 2014), e-methanol trucks are projected to have a 3-6% lower efficiency using a standard lean-burn diesel cycle (TNO, 2020c). The H_2-ICE concept is also expected to achieve an efficiency which is about the same as that of the diesel ICE (TNO, 2020b). It should, however, be emphasized that these engines are still in the early stages of development, and there are large uncertainties with the future projections.

For a reference long-haul diesel tractor-trailer, the assumed fuel consumption is 33.7 l/100km, equivalent to 3.4 kWh/km or 12.1 MJ/km. The projected energy consumption for all considered vehicle are reported in Table 4.

Table 4: Modelled energy consumption of an articulated tractor-trailer truck on a long-haul VECTO cycle (TNO, 2022).

Drivetrain	Unit	2020	2030	2040
ICE (diesel) - ref	l / 100km	33.7	27.5	27.5
ICE (diesel)	MJ / km	12.1	9.9	9.9
ICE (e-diesel)	MJ / km	12.1	9.9	9.9
ICE (e-DME)	MJ / km	12.1	9.9	9.9
ICE (e-LNG)	MJ / km	12.1	9.9	9.9
ICE (H_2)	MJ / km	12.1	9.9	9.9
ICE (e-methanol)	MJ / km	12.8	10.5	10.5
BEV (400 kWh)	MJ / km	4.7	3.9	3.8
BEV (750 kWh)	MJ / km	4.7	3.9	3.8
FCEV (H_2)	MJ / km	8.9	7.5	7.4

The final assumed values for the different powertrain alternatives are summarized in Figure 9.

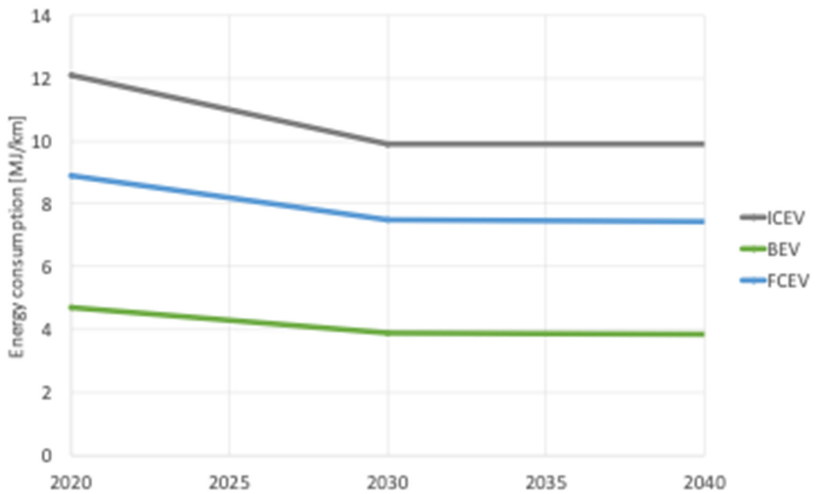

Figure 9: Energy consumption projections, modelled with ADVANCE for a long haul truck between 2020 and 2040.

4.1.3 Well-To-Wheel energy requirement

The combination of WTT and TTW energy requirement yields the total WTW energy demand of the entire energy chain (Figure 10). From an energy consumption point of view, direct electrification requires the least energy (both TTW and WTT). It requires approximately four times less energy than an equivalent truck on hydrogen or e-fuels. In case the energy carriers are transported over shorter distances or in case hydrogen is transported (partly) via pipelines, the energy chain efficiency of hydrogen improves compared to other energy carriers.

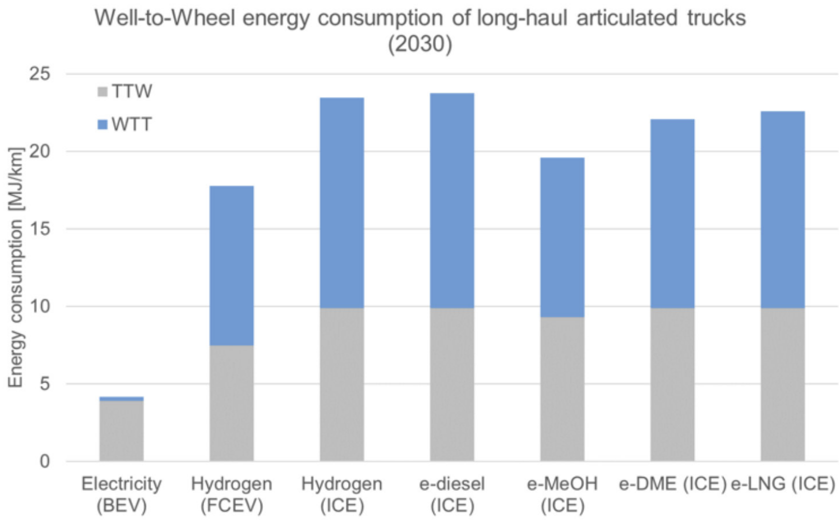

Figure 10: Total TTW and WTT energy consumption of a long-haul heavy-duty vehicle using different energy carriers for the 2030 energy requirement per kilometre projections.

4.2 Impact of the use of different energy carriers on total required energy

In this section, it is determined what it means if all long-haul tractor-trailers registered in The Netherlands would drive on the assessed energy carriers in terms of:

1) the surface of solar panels needed to produce the required electricity;
2) the installed power of wind turbines needed to produce the required electricity;
3) the number of electrolysis plants required;
4) household energy consumption equivalent.

The goal of this section is to get a feeling of the change in total annual primary energy consumption associated with the complete transition of all long-haul tractor-trailers in the Netherlands to any of the renewable energy carriers studied in this project, and of the energy production capacity that would be needed for the renewable options. A mix of two or more energy carriers is more likely. Additionally, not all energy carriers will necessarily have to be produced in the Netherlands. It is likely that a portion of the energy carriers will be imported, resulting in a lower domestic energy demand. For more information on the value chain of import or domestic production of energy carriers the reader is referred to (TNO, 2021c).

In the case that 100% of the tractor-trailers use a battery electric drivetrain the primary energy consumption is the lowest, whereas the primary energy consumption for 100% of the fleet on synthetic fuels is three to five times larger. The higher energy consumption is caused by larger energy losses during the production and transportation of the energy (WTT) and by less efficient drivetrains (TTW) compared to battery electric. The bandwidth originates in the uncertainties in the JRC study on the WTT side and potential improvements in the energy efficiency of the drivetrain.

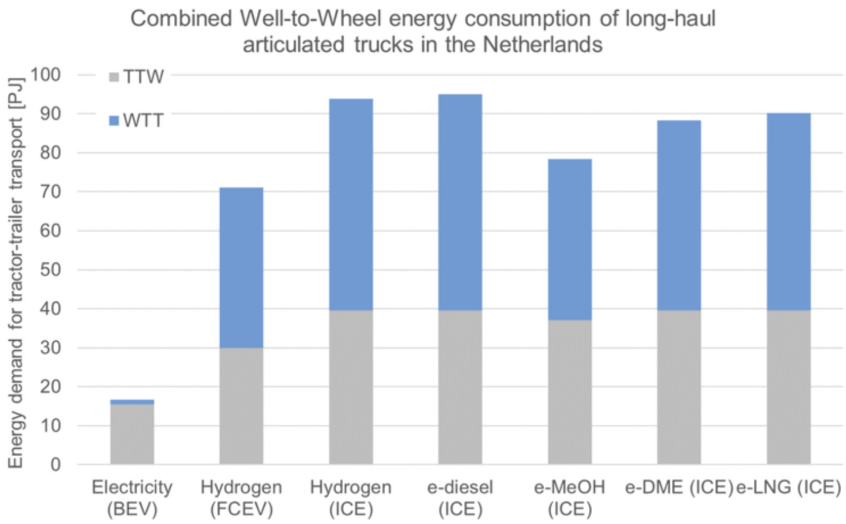

Figure 11: WTW energy demand of tractor-trailer transport (given a refence of 39 PJ TTW diesel).

In Table 5 the total energy demand depicted in Figure 11 is expressed in the amount of infrastructure needed for generation and conversion of electricity and is compared with the electricity consumption of households. The energy production of wind turbines installed in the Netherlands is currently approximately 2.5 GW in offshore wind parks[4]. The capacity on land is over 4.0 GW. To produce e-fuels for tractor-trailers only, 1.5 times the entire installed wind electricity production would be required[5]. In terms of solar panels, approximately 153 km^2 of solar panels is required to meet this energy demand.

Table 5: Infrastructural requirements for 100% transition towards one alternative fuel option and comparison with the electricity demand for households.

Equivalent to	**Electricity**	**Hydrogen**	**e-diesel**
Required (Figure 11)	16 PJ	70 PJ	94 PJ
Wind turbines[6]	2 GW	7.6 GW	10.2 GW
Solar panels[7]	27 km^2	114 km^2	153 km^2
Household equivalents[8]	6 mln	25 mln	34 mln

4 https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/windenergie-op-zee/windparken-op-de-noordzee

5 In (TNO, 2020d) the wind potential on the North sea for 2050 is estimated to be in between 60 GW and 200 GW, with a power output of 900 PJ to over 3,000 PJ

6 2559 full load hours per year (CBS, 2020)

7 170 kWh/m^3/year. Vattenfall – Excellent power Phono Solar 400Wp Full Black

8 2730 kWh/year (Nibud, 2021)

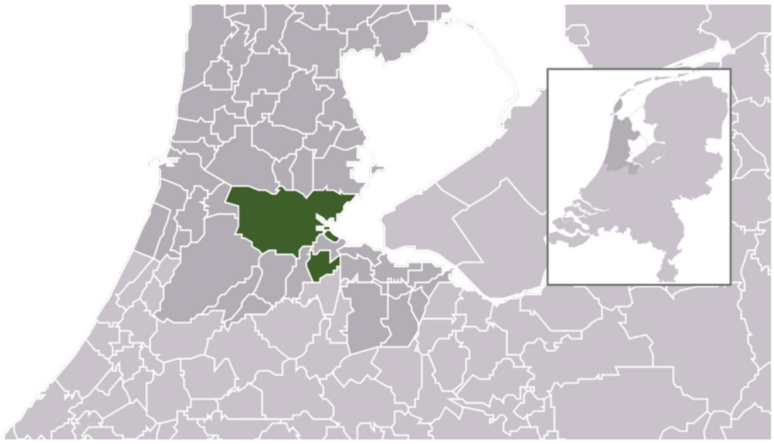

Figure 12: A comparison of required land area, approximately 150 km2 of net solar panel area is required for the production of hydrogen and/or e-fuels. The municipality of Amsterdam is 165 km^2.[9].

Furthermore, approximately 3.1 - 4.5 TW of electrolyser capacity is required to produce hydrogen, assuming a 70% yearly uptime and 50 kWh/kg hydrogen energy requirement (~67% electrolyser efficiency). In 2021 Shell opened Europe's largest hydrogen electrolysis plant, with a capacity of 10 MW in Germany[10]. This plant can produce 1.300 ton hydrogen per year. Approximately 200 of those plants are required for Dutch long-haul tractor-trailer traffic only, if 100% would drive on hydrogen fuel cells. Larger plants are being developed, for example, BP has plans for a 250 MW electrolysis plant in the Port of Rotterdam, with a production capacity of 350 kton/year (Topsector Energie, 2020).

4.3 Well-to-Wheel CO_2 emissions

There are different levels of CO_2 equivalent emissions associated with the considered fuels. Even though hydrogen fuel cell and electric vehicles have zero tailpipe emissions, there can still be CO_2 emitted during production and distribution of the energy carriers for example when hydrogen is distributed by diesel trucks.

The use of e-fuels leads to CO_2 emissions from the tailpipe because of the combusting a carbon-based fuel. However, if the carbon (CO_2) which is emitted has been extracted from the atmosphere to produce the fuel in the first place, the combustion CO_2 emissions can be considered net-zero.

4.4 Air polluting emissions

With e-fuels in an ICE engine there are still air polluting emissions such as NO_x or particulate matter (PM). Since the fuel is synthetic, the quality of the fuel can be higher resulting in somewhat less "engine-out" emissions. With modern vehicles, which are equipped with emission aftertreatment technologies such as SCR-deNOx catalysts and diesel particulate filters (DPF), the impact of fuel quality on exhaust emissions is very low. FCEV and BEV trucks do not cause polluting tailpipe emissions.

9 https://nl.wikipedia.org/wiki/Lijst_van_Nederlandse_gemeenten

10 https://www.reuters.com/business/energy/shell-opens-10-mw-german-hydrogen-electrolyser-boost-green-fuel-output-2021-07-02/

The pollutant emissions of a vehicle can only be regarded in combination with its after-treatment system. For both NO_x and PM, there are legal limits to which the powertrain must comply. According to the world harmonized standard WHTC, this is 0.46 g/kWh for NO_x and 0.01 g/kWh for PM for Euro VI heavy duty vehicles. For reasons given here below in the information box, all fuels will have similar pollutant emissions close to the legal requirements.

Disclaimer: The current European emission limits for pollutant emissions of heavy-duty vehicles (Euro VI) are very stringent and legally binding for all new powertrains and energy carriers. Whilst electric drivetrains, both battery and fuel cell, have no tailpipe emissions, ICEVs need to be equipped with emission aftertreatment technologies and advanced engine management strategies to comply to the emission limits. Given these legal boundaries, it is fair to assume that the tailpipe NO_x and PM emissions for ICEVs compared in this study will be roughly the same as those of diesel drivetrains (which meet the current limits). The only difference between the ICEV powertrains lies in the aftertreatment effort that needs to be taken to comply to these limits.

It is expected that for most of the ICEVs compared in this study, i.e., methanol, DME and LNG, the engine-out emissions will exceed the current Euro VI limits of NO_x and PM as well. This means that these drivetrains, like diesel, will have to be fitted with EGR (exhaust gas recirculation) and/or exhaust aftertreatment systems like SCR catalyst and particulate filters, so that the tailpipe emissions will meet the type-approval limits. For H_2-ICE it may potentially be possible to meet Euro VI limits without aftertreatment.

Diesel

The NO_x and PM_{10} exhaust emissions of a Euro VI diesel drivetrain are taken as the reference in this study. The real-world tailpipe NO_x and PM_{10} emissions of a compliant diesel Euro VI truck over the assumed distribution of road types in the Netherlands are approximately 1.08 g/km and 0.014 g/km, respectively. In practice, a diesel engine with Diesel Particulate Filter (DPF) can be lower in particulate number emissions than a spark ignition engine without DPF.

Methanol

A heavy-duty methanol vehicle can operate according to a mono fuel SI or dual fuel principle with both diesel and methanol. The engine-out NO_x emissions can be lower than diesel provided combustion temperatures are lower (Björnestrand, 2017). The PM_{10} emissions vary depending on the engine load and can be higher or lower than diesel PM_{10} emissions. It should be noted that methanol engines may have higher CO and HC emissions (Yao, et al., 2008).

DME

DME can be used in a monofuel configuration. The engine-out NO_x emissions for DME are expected to be lower than those of diesel (Thomas, Feng, Veeraragavan, Cleary, & Drinnan, 2014). The combustion of DME produces substantially lower levels of engine-out particulate emissions than diesel due to the high oxygen content (Szybist, McLaughlin, & Iyer, 2014). However, also DME engines will be developed to meet the legal limits and not significantly better than that. So, at end, it is expected that the emission level is similar to the diesel engine.

H_2-ICE

Various H_2-ICE engine concepts are currently being developed, e.g. port fuel injection (PFI) and direct injection (DI). Engines based on dual fuel port fuel injection seem to be closest to market at this point in time. Compared to the PFI, the DI concepts are expected to have relatively high NO_x emissions, like diesel. In these concepts H_2 is not pre-mixed with the air. This gives locally high combustion temperatures and thus high NOx emissions.

Like DME, hydrogen can also be used in a monofuel configuration in a compression ignition engine (H_2-ICE). The engine-out NO_x emissions for such a configuration are expected to be lower than those of diesel provided the combustion temperature is low (White, Steeper, & Lutz, 2006). However, to achieve low combustion temperatures a very lean burning configuration is necessary which may have disadvantages in terms of the transient response of the engine. Theoretically, the combustion of hydrogen produces no engine-out particulate emissions. However, the presence of lubricants in the combustion chamber and potentially impurities in the fuel can lead to low levels of tailpipe PM_{10} emissions (White, Steeper, & Lutz, 2006). It is expected that the emission control equipment will be less extensive and costly than with diesel engines.

-05-

Total mobility chain costs

In this chapter the total chain costs of the various drivetrains and energy carriers are compared from a societal perspective. This means that taxes (on fuels and vehicles) are not included. This societal perspective is most appropriate for this study as the development of tax levels on these alternative energy carriers is unknown. For instance, in the Netherlands, there is currently no energy tax or excise duty on hydrogen[11]. However, in case hydrogen would substitute a significant share of fossil fuels, some form of taxes may be introduced in the future to ensure sufficient government tax revenues. The comparison is made based on the Total Cost of Ownership (TCO) of a tractor-trailer truck driving 100.000 km annually.

In Section 5.1 the capital expenditures (CAPEX) are determined for the various tractor-trailers. The investment costs are based on the production costs of the vehicles and are determined bottom-up. The section begins with a description of the methodology, and further summarizes the assumptions and final values obtained for all the types of tractor-trailers. Section 5.2 analyses the operational expenses (OPEX). This includes the cost of the fuels (further subdivided into the costs of the production of the fuel, delivery cost, refuelling stations, maintenance, and insurance. Section 5.3 presents the combined TCO projections from a societal perspective.

Disclaimer: It is important to emphasize that cost is not the same as price. This is relevant to all topics discussed in this chapter. Technical potential regarding cost is not the only driver in a large global market. Taxes have not been considered in the analysis since information on how future fuels are taxed is unknown. Predictions of price levels more than ten years into the future are inherently uncertain, external factors such as supply and demand or profit margins are not taken into account.

The TCO comparison is calculated based on expected costs for 2030, since large scale production of e-fuels and green hydrogen is currently not existent. A TCO for 2020 is presented for illustrative purposes. The goal of this chapter is to provide cost levels based on technical potential and determine the order of magnitude impact of cost components on the final TCO. In Figure 13, the breakdown of the TCO model is presented.

11 Electricity or natural gas used for the production of hydrogen is taxed

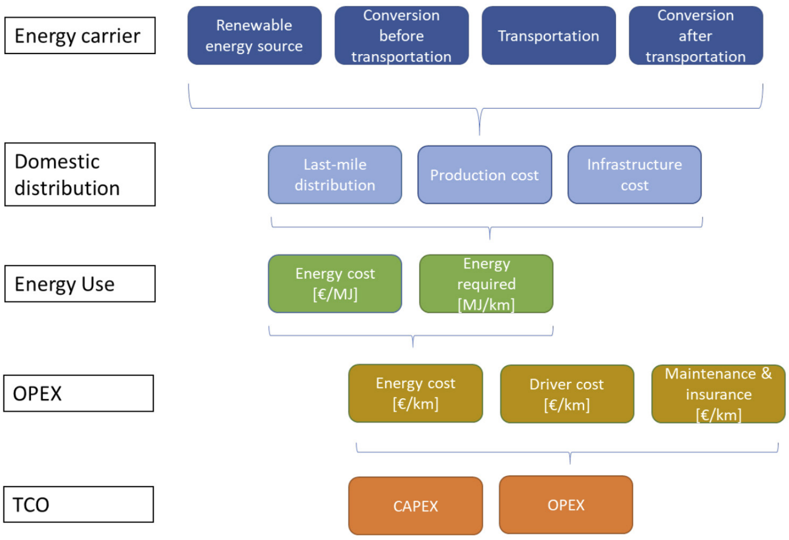

Figure 13: Value-chain cost model breakdown.

5.1 Vehicle cost projections

The model to calculate the production costs of the vehicle is based on a disaggregation of the vehicle to its component/sub-system level and an analysis of the available literature for current and future projected prices (2020-2040). The cost of the vehicle is the sum of the cost of the glider and the costs of all powertrain components. The vehicle capital expenditure is described in more detail in (TNO, 2022) and is illustrated in Figure 14.

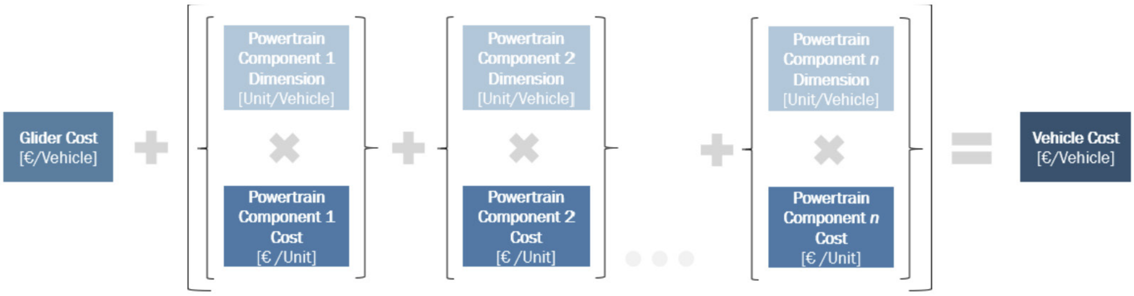

Figure 14: Vehicle cost model.

The detailed costs for each component/sub-system as well as considered sensitivities are listed in Appendix B, while the core assumptions and sensitivities are discussed in the subsequent sections.

The configuration of each powertrain is defined based on operational, legal and technological restrictions; volume and weight constraints; as well as a benchmarking exercise with state-of-the-art trucks available in the market.

5.1.1 Fixed component cost

Table 6 provides an overview of the subcomponents in the vehicle cost-model. The component costs are either fixed or scale with vehicle characteristics (such as engine power or battery capacity). Component cost reductions over time are included due to technical improvements and effect of scale.

Table 6: Components considered in the bottom-up cost analysis for the various drivetrains.

Input parameter	ICE	BEV	FCEV
Glider	x	x	x
Trailer	x	x	x
Battery	-	x	x
Fuel storage	x	-	x
Drivetrain (engine, gearbox, etc)	x	-	-
Fuel cell	-	-	x
Energy reducing technologies	x	x	x
Other components (e.g., DC/DC converter, onboard charger and airco/ heatpump compressors)	x	x	x
Mark-up factor	x	x	x

The higher price of alternative propulsion technologies is further exacerbated by the smaller economies of scale due to limited production amounts, as well as uncertainties involving future developments in technology. The estimation of the vehicle purchase price is further determined by the costs arising from manufacturing, R&D and additional expenses involved in the manufacturing chain.

Prices may differ from costs as a result of company strategies – where the profit margin on one model/ drivetrain technology might be reduced to promote sales, while this is balanced by the sales of more established models. This phenomenon is also known as cross-subsidising. Together these factors also have a cyclical effect – for instance, a slower development of hydrogen fuel cell technology would imply a higher vehicle cost, leading to lower demand and therefore smaller production scales, which in turn hampers the further reduction of production costs. A variable mark-up factor is assumed over time is applied to account for this effect as is shown in the figure below.

For diesel trucks the mark-up factor in 2020 is obtained by assessing the difference between the calculated production cost and typical market prices. This results in a mark-up factor of 1.19 for diesel trucks. For zero-emission vehicles the assumed factor 1.4, based on a recent study by the ICCT (Sharpe, 2022). For the alternative drivetrains, the mark-up factor for 2020 is significantly higher due to lower production volumes. For instance, current production of electric trucks is partly done outside of the main production lines. This takes additional time and manual labour, resulting in higher production cost and therefore a higher mark-up factor.

Towards 2040 the production volumes of diesel trucks are expected to decrease in favour of that of zero-emission trucks. This is assumed to result in an increasing mark-up factor for diesel trucks and an decreasing factor for zero-emission trucks. The mark-up factor of the various drivetrains is assumed to be eventually equal for all, at an estimated value of 25%.

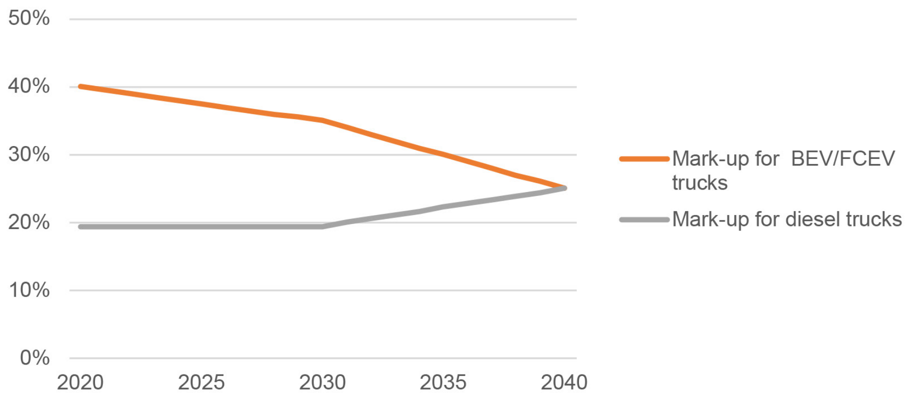

Figure 15: Mark-up factor projection assumptions used for the cost-modelling in this study (TNO, 2022).

5.1.2 Battery cost

The central scenario for heavy-duty battery cost is obtained from (TNO, 2022) which is based on battery costs projections by Bloomberg New Energy Finance (BNEF) projections (BNEF, 2021). This projection includes future developments such as the inclusion of the battery in the vehicle chassis which results in further cost reductions.

Since battery costs is a substantial factor in the final vehicle price, a sensitivity analysis is conducted to account for the large variation in costs reported in literature for the batteries.

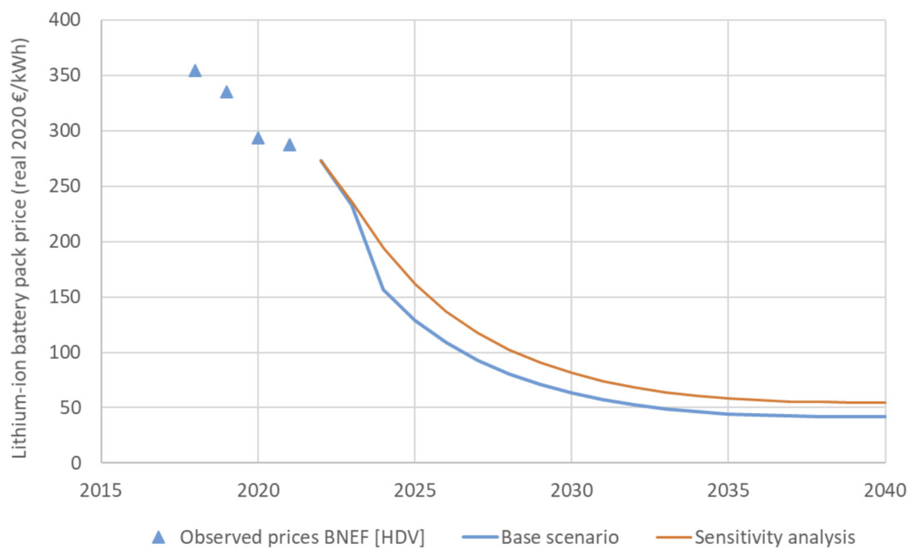

Figure 16: Battery pack price projection based on BNEF, edits by TNO (TNO, 2022).

The central scenario as well as high values used in the sensitivity analysis are summarized in Table 7.

Table 7: Summary of battery costs used for different cost scenarios for 2020, 2030 & 2040.

Battery costs [€/kWh]	2020	2030	2040
High	293	81	55
Central	293	63	42

5.1.3 Hydrogen fuel cell

The fuel-cell stack forms a particularly sensitive component, as illustrated in Figure 17. A large variation is observed in the reported values in literature for the fuel-cell stack, partly since some sources report on cell level while others report on system level. For this reason, a sensitivity analysis has been included with low and high hydrogen fuel cell prices. Higher production volumes in the future as well as technological improvements can drive the price downwards.

Based on sources found in the literature review that do provide the assumed production scale necessary to reach a given cost (Roland Berger, 2020)(James B. D., 2021)(James B. D., 2018), combined with assumptions for production levels a cost development curve for fuel cells has been assumed. The reductions in the cost development for fuel cells towards 2030 are in line with the projections made by Ricardo (2021), see also (TNO, 2022).

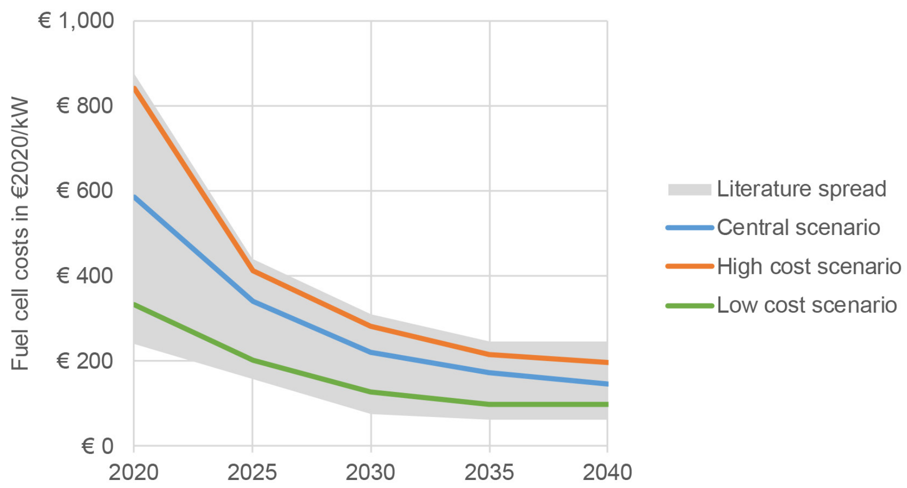

Figure 17: Fuel-cell (system-level) cost projections and literature spread (TNO, 2022).

In the Table below the fuel-cell costs as used in this study can be found for 2020, 2030 and 2040 for the high and low scenarios.

Table 8: Projected fuel-cell stack system level cost.

Fuel cell [€/kW]	2020	2030	2040
High	841	280	194
Central	586	220	145
Low	330	125	96

5.1.4 Engine Costs

The engine costs are assumed to remain constant over time, reflecting the relatively saturated state of development.

5.1.5 Component costs

There are several other fixed costs such as the glider, the trailer, energy reduction technologies but also more specific costs such as DC/DC converters, onboard chargers, fuel storage and emission control systems.

The glider is one of the fixed costs of the vehicle. It consists of the vehicle chassis and the cab, excluding the drivetrain. The glider cost are similar for all vehicles to a large extend. For the ICE vehicles, a number of auxiliary functions are combined to the diesel engine (for instance the cabin is heated using waste heat from the engine). The electric trucks cannot use the waste heat and therefore the auxiliary systems are added separately. To account for this, multiple additional systems need to be included (such as heating pump, electric air brake compressors) separately, resulting in a lower glider cost.

Apart from auxiliary systems necessary for al drivetrains also other, more drivetrain specific components necessary to operate the vehicles are included. For a diesel truck this includes for instance a fuel tank and emission control systems, while for a hydrogen truck this is a hydrogen tank and for an electric truck this could be an onboard charger. The emission control system cost for 2020 is based on a Euro VI SCR system (Fries, et al., 2017), and the cost is assumed to rise by 30% from 2020 to 2030 (assumption based on expert consultation), to account for increasingly stringent emission regulations (Euro VII). This leads to an increase in the overall cost of the vehicle.
An overview of sources for the glider and the auxiliary components are provided in (TNO, 2022).

Trailer
The assumed costs of a single trailer are € 26,049 based on three recent studies by the ICCT (2021b) (2018) (2017). For the articulated trucks, a trailer-to-tractor ratio of 1.4 is used. This value is based on a 2018 study by the ICCT (Mezsler, Delgado, Rodriguez, & Muncrief, 2018). This entails that all costs related to trailers will be multiplied by 1.4 to account for the fact that each truck uses approximately 1.4 trailers, including the costs for technology reducing options. (TNO, 2022)

Energy reduction
Towards 2030 more technologies are applied in the heavy-duty vehicles and the penetration level to increase fully towards 2030. The costs of the energy reducing technologies are based on a previous study by TNO (TNO, 2018).

5.1.6 Vehicle cost: ICE

The ICE tractors are sized according to state-of-the-art values reported by several manufacturers for long-haul tractors, as reported in Table 9.

Table 9: Diesel ICE tractors specifications benchmarking.

Parameter	Used	DAF XF	Mercedes-Benz Actros L	Volvo FM
Power [kW]	350	270-390	240-460	246-372
Fuel Tank [L]	600	Custom		

The tanks for the ICE tractors using e-LNG are based on the typical intermediate tank size reported by OEMs, translating to a tank of 155 kg capacity[12]. The e-DME vehicle is assumed to use a similar pressurized system, and therefore, a similar tank capacity. The cost for the e-LNG trucks is estimated to be about €30,000 higher than a comparable diesel truck (TNO, 2020c). While the cost of an e-methanol and e-DME trucks are estimated to be about €7,500 higher than the standard diesel trucks (TNO, 2020c; Styring, Dowson, & Tozer, 2021).

Table 10: Cost projections for tractor ICE configurations (values in k€).

Vehicle type	2020	2030	2040
ICE (e-)diesel	143	158	169
ICE e-LNG	173	188	199
ICE e-DME/e-Methanol	151	166	177

12 https://stpi.it.volvo.com/STPIFiles/Volvo/FactSheet/LGAS115,%20LGAS155,%20LGAS205_Eng_01_309253877.pdf

5.1.7 Vehicle cost: battery electric

In Table 10 an overview of BEV tractor-trailers from various OEMS and literature sources is provided. In this study two tractor-trailer versions are used with a 370 kW electric motor and 400 kWh or 750 kWh battery. With an approximate range of 300 km or 500 km, respectively (TNO, 2022).

Table 11: BEV tractor-trailer specifications and benchmarking with OEMs/literature.

Vehicle type	Electric Motor [kW]	Battery Capacity [kWh]
Used	370	400-750[13]
Tesla Semi	N/A	500-800[14]
Volvo FH Electric	330-490	180-540
Nikola Tre BEV	480	753
Freightliner e-Cascadia	268-373	530
Topsector Logistiek[15]	300	440
TNO[16]	330	400

The sizes of these battery packs are based on a review of the vehicles being proposed by various manufacturers, as reported inTable 11. These values are further ratified by a bottom-up analysis based on the restrictions posed by Article 7 of the European Regulation 561/2006. This regulation mandates a 45 minute break after each 4.5 hours of driving. Therefore, the large battery case is designed to allow for continuous driving for the 4.5 hours (~400 kms), with a small buffer to account for hilly/mountainous terrain17. This allows the incorporation of BEVs into the fleet with minimal operational changes, assuming that sufficient recharging infrastructure is available.

It is expected that as the market matures, several configurations of battery electric vehicle tractors will emerge to serve different applications. In low-mileage scenarios, fleet operators might opt for smaller battery sizes, thereby limiting the capital costs and empty weight of the vehicle. For longer daily distances tractors with smaller batteries result in higher operational cost due to the reliance on (fast) charging during the day.

Table 12: Projected BEV tractor-trailer cost (values in k€).

Vehicle type	Scenario	2020	2030	2040
BEV (400 kWh)	High	343	197	171
	Central	343	187	164
BEV (750 kWh)	High	487	235	195
	Central	487	217	183

13 Assumed value for 2020. The battery capacity is assumed to increase over time, to maintain the same weight for the same overall weight of the battery.

14 Best industry estimates based on claimed range from the OEM.

15 (Topsector Logistiek, 2020)

16 (TNO, 2021b)

17 Sample calculation: Desired Battery Size = [Desired range (assumed to be 400km))*(Energy consumption of the truck (1.5kWh/km)]/(Usable battery capacity). Here desired range is computed as the distance travelled at an average highway speed of 80 km/h over a continuous driving time of 4.5 hours, with an additional 10% buffer.

5.1.8 Vehicle cost: fuel-cell electric tractor-trailer

The hydrogen tank and the battery capacity are sized using a bottom-up analysis, based on the available space in the vehicle. It is assumed that the volume of the fuel-tank and the engine of diesel ICE tractor can be used for the alternative powertrain components, such that a technically feasible solution is reached.

There is a large variation in the type and configuration of fuel-cell tractors proposed by various OEMs and researchers, particularly in terms of the power of the fuel cell stack, the size of the hydrogen tank and the capacity of the battery, as reported in Table 13. Given these large variations, each choice is duly discussed and motivated in the following paragraphs.

Table 13: FCEV tractor specifications and benchmarking with OEMs/literature.

Vehicle type	Fuel Cell Stack Power [kW]	Hydrogen Tank Capacity [kg]	Electric Motor [kW]	Battery Capacity [kWh]
Used (700 bar)	240	60	370	140
Mercedes-Benz Gen-H_2 (Liquid H_2)	300	70	460	70
Nikola Tre and Two (700 bar)	200-300	70[18]	480	?
Topsector Logistiek (700 bar)[19]	300	100	300	250

The choice of H_2 storage is driven by positive trends in the technological development of high-pressure (700 bar) H_2 tanks and distribution systems. The experts consulted expressed concerns on the applicability and scalability of cryogenic (liquid) H_2 setups in the near future. The fuel-cell stack and motor powers are maintained to values in line with those proposed by various OEMs and researchers. The final vehicle costs are computed and reported in Table 14.

Table 14: Projected FCEV tractor costs (values in k€).

Vehicle type	Scenario	2020	2030	2040
FCEV	High	579	294	241
	Mid	494	274	226
	Low	408	243	211

5.1.9 H_2-ICEV tractor-trailer cost

The H_2-ICEV is defined (both in terms of configuration and vehicle cost) by replacing the diesel fuel-tank with the hydrogen tank assembly, as in the FCEV section, leading to an overall capacity of 70 kg H_2[20].

Furthermore, it is expected that for the long-haul heavy-duty case, a high-pressure direct injection system would be the ideal choice, because of the higher efficiency. In such a case, eliminating the after-treatment system may not be possible due to the presence of NO_x emissions. The Diesel Particu-

18 Best-estimate values based on the reported range by the OEM. It should be noted that Nikola defines a configuration based on the US market. Therefore, they also use tanks mounted on the back of the cabin, which would flout the length restrictions in the EU. Therefore, a smaller tank size is needed in the EU.

19 (Topsector Logistiek, 2020)

20 Note that this is more than the tank size used in the FCEV (45 kg), since a high-voltage battery pack is not required in this case. Therefore, more hydrogen tanks can be accommodated.

late Filter (DPF) would not be required due to the absence of CO_2 in the exhaust. Although a system like the Diesel Oxidation Catalyst (DOC) may be required to counter possible hydrogen slip, the size of such a system is smaller than that of a comparable diesel-ICE. Therefore, the expected costs for the emission after-treatment system are likely to be much lower than that for the diesel ICE.

However, given that this is still a very nascent field of research, supporting literature for component-wise prices is not yet available. Instead, the prices for the components have been estimated based on the consultation of experts from the TNO Powertrains Centre. The expected cost for the after-treatment system is between a third and a half (the latter of which has been accepted as a conservative estimate) that of the cost for a comparable diesel ICE. It should be noted that these are initial ballpark estimates, and require more research for scientific certainty.

A sensitivity analysis is conducted for the hydrogen tank cost, thereby providing a bandwidth for the H_2-ICE truck costs, as demonstrated in Table 15.

Table 15: H2-ICE tractor cost projection (values in k€).

Vehicle type	Scenario	2020	2030	2040
	High	195	167	148
ICE-H_2	Mid	165	148	140
	Low	155	144	136

5.2 Operational cost

The operational cost (OPEX), which are considered in this analysis, are composed of the energy cost (production, distribution, and infrastructure), maintenance and insurance.

5.2.1 Cost of energy carrier production and import to The Netherlands

In this study the results regarding the fuel cost of the CHAIN study (TNO, 2021c) are used as an input for the energy cost part of the cost breakdown. For e-fuels, the most economic option was concluded to be importing from abroad from regions with lower electricity costs. On the contrary, for hydrogen it has been concluded that domestic production is the most economical option, due to the relatively high cost related to transport cost for the import from abroad. Within in this study no additional analysis has been made regarding cost developments from 2030 onwards. In another recent TNO study (TNO, 2022b), 2040 cost estimates for only e-methanol are available based on the same methodology as the 2030 cost.

In Table 16 the used energy costs are presented based on the following conclusions from (TNO, 2021c):

- Production of e-diesel via the methanol route is found most efficient and results in lowest cost. Cost of production via Fischer-Tropsch[21] is close to the cost of the methanol route.
- Import of e-diesel is significantly more cost effective than local production of both intermediate and fuel, but only slightly more cost effective than producing the fuels locally from imported intermediates, such as methanol or Fischer-Tropsch-crude.
- Import of Fischer-Tropsch-crude presents technical challenges. Also, the step from intermediate to diesel (and kerosine) results in a higher value product, while the additional expenses are limited. It seems logical that the producer of the intermediate converts it into the final e-diesel product. Import

21 The Fischer-Tropsch process is a number of chemical reactions in which carbon monoxide (CO) and hydrogen (H_2) are converted into liquid hydrocarbons.

of green e-methanol to produce diesel seems more rational, since methanol is also a platform molecule for the chemical industry and a global methanol market already exists.

The cost of e-DME were not part of the CHAIN study (TNO, 2020c). The production cost for e-DME is derived from the production cost of e-methanol with an additional 7% cost increase for the extra energy required for the final transformation step from methanol to DME (JRC, 2020c).

The costs for e-LNG import are derived from a route in the CHAIN study (TNO, 2020) in which e-LNG is imported to the Netherlands and further processed there to e-diesel.

Just like the e-fuels, the production cost projections of green hydrogen are only available up to 2030. In a recent TNO study (TNO, 2021e), hydrogen production cost projections by TNO are compared to projections in various other literature sources (see Figure 18). It is concluded that the TNO projections are significantly higher for 2020 and 2030 because of several reasons further explained in the TNO report. Beyond 2030 cost projections by other organisations are available, but projections by TNO are not. Due to the difference is cost projections in 2020 and 2030, using 2040 cost projections from other literature sources would lead to an unbalanced comparison.

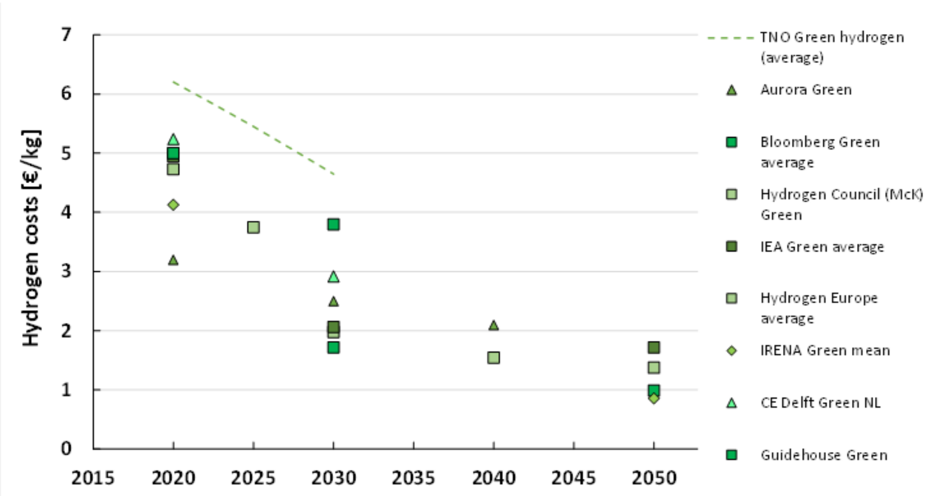

Figure 18: Production cost projections for green hydrogen from recent literature sources.

In Table 16 the energy production and cost for import to The Netherlands, as used in this study, are summarized. As explained above, for 2040 only e-methanol cost are included as the cost of the other fuels are not available from sources that are based on the same methodology and are therefore consistent with the other production cost values used.

Table 16: Production cost results for various energy carriers.

Year	Fuel	€/GJ	€/kWh	€/kg	€/l
2020	Hydrogen (domestic)****	64	0.23	6.2	-
2030	Hydrogen (domestic)	39	0.14	4.7	-
	e-diesel (e-diesel import)	51	0.18	2.2	1.82
	e-methanol (e-Methanol import)	44	0.16	0.9	0.69
	e-DME (e-DME import)*	45	0.16	1.3	0.86
	e-LNG (e-LNG import)	83	0.30	4.5	1.83
2040	e-methanol (e-methanol-import)	41	0.15	0.8	0.65

* costs for conversion from e-Methanol to e-DME estimated based on ratio between efficiency and cost of conversion from H_2 and CO_2 to e-Methanol.
** based on literature sources mentioned in TNO, 2022
*** based on literature sources mentioned in TNO, 2022 increased by relative difference between TNO projection and literature for 2030
**** based on (TNO, 2021e)

5.2.2 Distribution costs within The Netherlands

The second factor considered in the fuel cost breakdown are distribution costs within the Netherlands. For e-fuels this includes the transportation from the site where the fuel is imported to the refuelling stations. For hydrogen this is the distribution from the production location to the refuelling stations.

Eventually, the distribution of energy carriers towards the refuelling stations needs to be executed without any emissions, using zero-emission trucks or pipelines instead of diesel-powered tanker-trailers. Since these trips are relatively short and there will be time to recharge as the trucks are being unloaded[22] in this study it is assumed that the distribution of fuels within the Netherlands will be conducted by BEV tanker-trucks. Therefore, the TCO of the BEV truck is computed first, after which the energy distribution costs are calculated to determine a TCO for all other energy carriers.

5.2.2.1 Energy per truck load

The distribution cost of energy carriers (e.g., e-methanol, e-diesel, e-DME and hydrogen) is sensitive to the volumetric energy density. Due to the lower volumetric energy density of hydrogen, e-methanol and e-DME compared to (e-)diesel, less energy can be transported per truckload. As a result, the price per unit of transported energy is higher. In Table 17 the assumptions regarding energy delivery are summarized:

- For the transportation of hydrogen, a 1000 kg tube-trailer is assumed.
- A diesel trailer with a capacity of 30-ton fuel is used as a reference for e-Methanol and e-DME[23].

Table 17: Gravimetric and volumetric energy densities defining the stored energy potential in a fuel trailer.

Parameter	Unit	e-diesel	e-MeOH	e-DME	e-LNG	H_2
Energy density	MJ/kg	43.1	19.9	28.4	53.6	121
Density	kg/litre	0.83	0.79	0.67	0.41	-
Tanker capacity	ton/truck	30	28.6	24.1	14.8	1.0
Tanker capacity	GJ/truck	1293	569	685	637	121

It can be concluded from Table 17 and Figure 19 that, given the same tank volume, a truck transporting e-methanol or e-DME can only deliver approximately half the energy compared to a diesel truck. A 1000 kg H_2 tube-trailer contains approximately 10 times less energy than a truck transporting diesel.

22 This does require an extra safety analysis and recharging infrastructure needs to be available.
23 Transportation of e-DME will most likely be more comparable to the current transportation of LPG as a liquefied gas under moderate pressures..

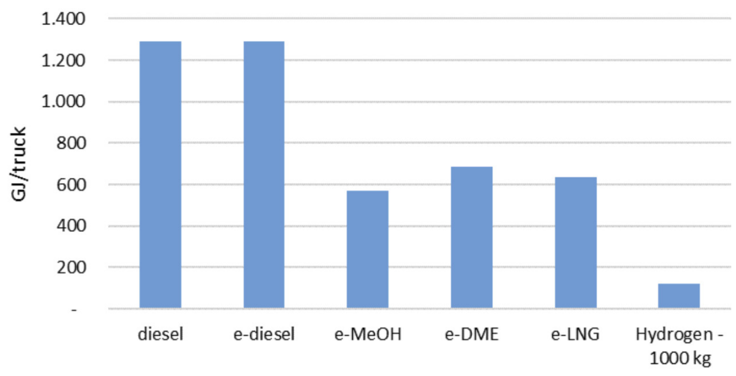

Figure 19: Energy capacity comparison for the distribution of various fuel types by trucks.

Projections for future hydrogen tractors indicate that their on-board storage capacity will be approximately 70 kg for H_2-FCEV trucks, as explained in Section 5.1.8. Given a transportation capacity of 1,000 kg hydrogen in a tube-trailer, approximately 14 trucks can be refuelled per delivery, and this is enough for about 12,375 truck kilometres (at 8 kg/100 km). In comparison, 30,000 litres of diesel (transported in one truck load) can achieve about 100,000 truck kilometres (at 30 litres/100km).

5.2.2.2 Costs of distribution by truck

e-DME is gaseous at room temperature, but it is transported as a liquid in pressurized tanks comparable to LPG transport. Since methanol is a liquid at standard conditions it is assumed that the transportation is similar to diesel transportation. Safety concerns might influence this assumption as will be addressed in Chapter 6.

A price of €18,500 for a distribution trailer for liquids is assumed for the (e-)diesel and e-Methanol tanker trailer. The e-DME and e-LNG trailer are assumed to be twice as expensive. For the compressed hydrogen tube-trailer, with a capacity of 1,000 kg, a CAPEX of € 600,000 is used in this analysis, based on (Wittkampf & Kleiburg, 2019). Another projection for hydrogen tube-trailers finds a trailer cost of $420,000 with a capacity of 880 kgH_2 (Houchins & James, 2020). In Table 18 an overview of the distribution cost breakdown and assumptions is provided.

Table 18: Distribution cost results for 2030.

Parameter	Unit	e-diesel	e-MeOH	e-DME	e-LNG	H_2
Energy cost (electricity)	€/kWh	0.15	0.15	0.15	0.15	0.15
Energy consumption	kWh/km	1.08	1.08	1.08	1.08	1.08
Energy cost electric truck	€/km	0.16	0.16	0.16	0.16	0.16
CAPEX trailer	k€	18,5	18,5	37	600	37
CAPEX e-truck[24]	k€	178	178	194	757	194
Depreciation period truck	year	8	8	8	8	8
Depreciation e-truck + trailer	k€/year	20	20	23	100	23
Operation and maintenance (including driver)	k€/year	68	68	68	68	68
Mileage	km/year	50.000	50.000	50.000	50.000	50.000
Cost per km	**€/km**	1.91	1.91	1.97	3.52	1.97

24 Middle scenario for an 2030 e-truck with a small battery (2030).

The cost of distribution in the Netherlands is computed to be 1.9 €/km for a liquid fuel distribution truck and 3.5 €/km for the compressed hydrogen truck over the lifetime of the battery-electric distribution truck in 2030. Per delivery a fixed additional fee of € 250 is calculated (TNO, 2020c). In Table 19 the trip cost expressed in cost per GJ of energy delivered are presented.

Table 19: Projected 200 km roundtrip delivery cost for 2030.

		e-diesel	e-methanol	e-DME	hydrogen	e-LNG
Roundtrip	km	200	200	200	200	200
Fixed additional delivery cost	per trip	250	250	250	250	250
TCO distribution truck (2030)	€/km	1.91	1.91	1.97	3.52	1.97
Roundtrip cost	€	633	633	643	954	643
Energy delivered	GJ / truckload	1293	569	685	121	637
Total delivery cost	€/GJ	0.49	1.11	0.94	7.88	1.01

With an assumed roundtrip delivery distance of 200 km the cost of a hydrogen delivery is €950 per delivery. For a 1000 kg hydrogen delivery this amounts to approximately 8 €/GJ (approximately 1 €/kg). For the other e-fuels the delivery cost is substantially lower at approximately 0,5 - 1 €/GJ. Even though the hydrogen trailers are more expensive than the other trailer options, the difference in price is due to the smaller amounts of energy that can be transported.

For hydrogen distribution one delivery of 1,000 kg per hydrogen truck is assumed. Due to the long filling time for the trailer tanks, multiple tube-trailers may be required to allow for 'trailer-swapping' such that one trailer can be refilled while the other is on its way to or at a hydrogen refuelling station. Therefore, the cost-estimates used here for hydrogen delivery may be considered optimistic.

5.2.2.3 Hydrogen distribution by pipeline

Pipeline costs depend on several factors. The main cost factors are found in the total distance of the pipeline and the capacity of the pipeline. In literature, the price of hydrogen pipeline is compared to the price of natural gas pipeline.

The cost of the hydrogen pipeline is determined based on separate data fits to natural gas pipeline labour costs, miscellaneous costs, right of way costs and material costs derived from (Parker, 2004). The main difference is a factor 1.5 in the material cost of hydrogen pipelines due to the higher embrittlement risk with hydrogen transport (Ogden, 1999) (Parker, 2004). An error margin is applied on each separate cost component of the model. The model used in this study is based on the assumptions and method from (Parker, 2004).

The diameter of the pipeline is coupled to the design capacity by a maximum flow velocity of 20 [m/s] (Toolbox, 2014) and an energy density of 13 MJ/m^3 (Zabrzeski, Janusz, Blacharski, & Kaliski, 2016). The total OPEX is assumed as 5% of the CAPEX (Yang & Ogden, 2006) and the pipeline economic depreciation period is assumed to be 40 years (Smit, Weeda, & Groot, 2006). The daily hydrogen demand and the maximum flow rate determine the required pipeline diameter, which in turn is a driving factor for the pipeline cost per kilometre. The model flow diagram is visually presented in Figure 20.

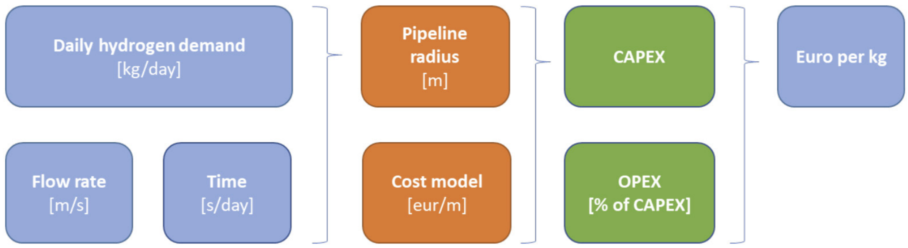

Figure 20: Hydrogen pipeline cost model.

The calculated pipeline transport costs per kg H_2 are shown in the figures below. It can be concluded that for low capacities the compressed hydrogen truck transport remains beneficial even at longer transport distances. Hydrogen transport by pipeline becomes economically beneficial compared to delivery by truck for increasing capacities and shorter distances. For short pipeline distances, hydrogen delivery by pipeline is more cost competitive due to lower total material and labour cost.

Hydrogen purification cost
Cost for purifying hydrogen to levels that are required for fuel cells are not included in this analysis. Therefore these conclusions are only valid for the situation in which the purity of the distributed hydrogen is sufficient for the vehicles. In reality purification may be required for the use in fuel cells.

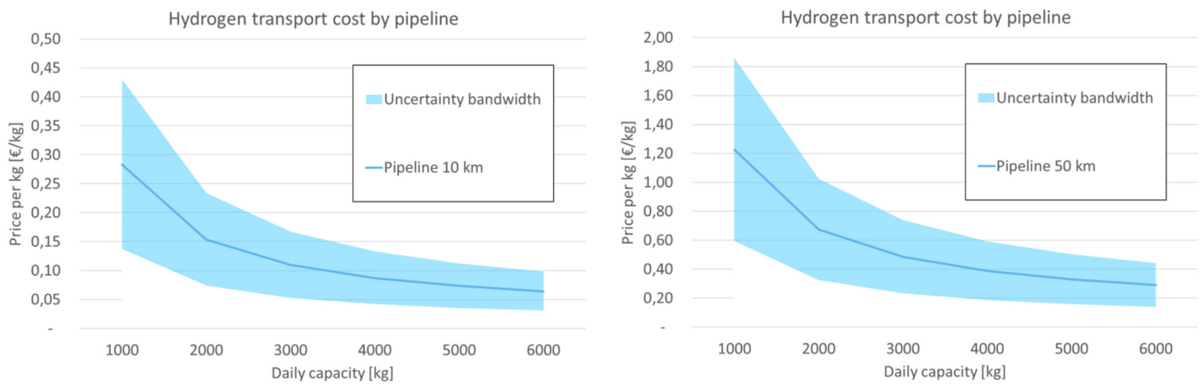

Figure 21: Pipeline cost estimation for a 10 km and a 50 km pipeline

It is worth mentioning the alternative strategy of converting existing natural gas pipelines for the transport of hydrogen. According to the European hydrogen backbone report of 2020, this strategy enables a capital cost reduction of 10%-25% compared to the construction of new hydrogen pipelines (Wang, Leun, Peters, & Buseman, 2020). Converted pipelines should be operated at lower pressures due to accelerated embrittlement of the pipeline with hydrogen. Alternatively, an internal coating is required to solve this problem. The estimated levelized costs based on 48-inch, 23,000 km long pipeline is given between 0.07 and 0.15 €/kg/1000km.

In this example a pipeline length of 50 kilometres is assumed. An effective cost reducing method is to place the hydrogen refuelling station close to a hydrogen backbone to reduce the additional infrastructure cost. Currently Gasunie is working on plans to develop a hydrogen backbone in the Netherlands, using the existing natural gas pipelines[25]. It is worth exploring the potential synergy with hydrogen refuelling stations in the near future.

25 https://www.gasunie.nl/en/expertise/hydrogen/hydrogen-backbone

5.2.3 Refuelling stations for carbon-based e-fuels

It is assumed that with minimal extra capital expenditure the existing diesel or gasoline and LPG tank infrastructure can be repurposed towards alternative synfuels such as e-diesel or e-DME and e-methanol. Because e-DME and e-methanol have lower energy densities compared to diesel, trucks will need to refuel more frequently. This may result in more refuelling stations or higher occupancy rates. Nevertheless, this effect is not explored, and it is assumed that no additional infrastructure is needed for e-DME and e-methanol. The operational cost assumptions are summarized in Table 20 and are based on (TNO, 2020c).

Table 20: Additional operational cost of the refuelling infrastructure for carbon-based e-fuels, based on (TNO, 2020c).

Parameter	e-diesel	e-methanol	e-DME	e-LNG
Cost (€/kg)	0.04	0.04	0.04	0.20
Cost (€/GJ)	0.9	2.0	1.4	4.0

21 Hydrogen refuelling stations (HRS)

Since the required refuelling facilities for hydrogen are fundamentally different from those for the other e-fuels considered, only for hydrogen the tank infrastructure costs need to be worked out in detail. For the investment cost of a hydrogen refuelling station (Figure 22) an interpolation is made based on the analysis in the impact assessment for the Alternative Fuel Infrastructure Regulation (AFIR) by Ricardo in 2021 (Ricardo, 2021).

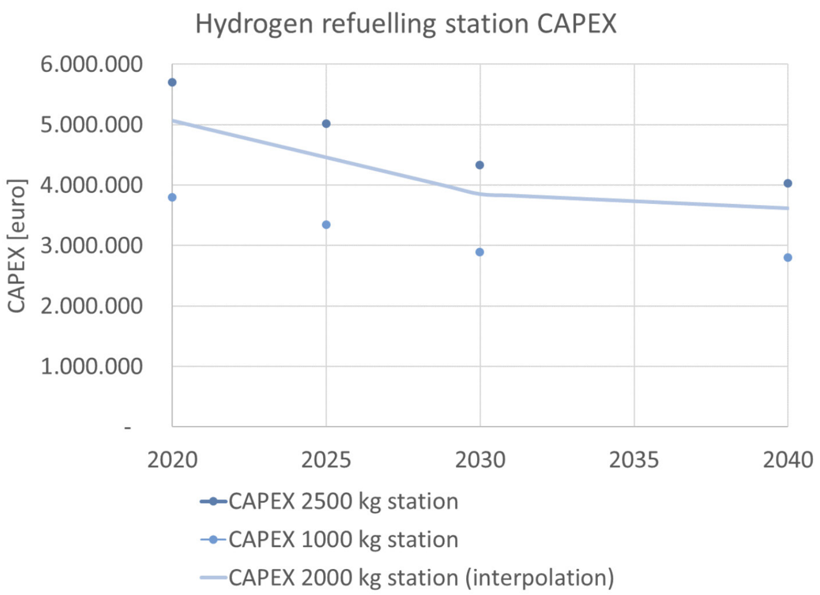

Figure 22: CAPEX for a hydrogen refuelling station based on (Ricardo, 2021).

The assumptions used to convert the investment cost into an additional cost per kg of hydrogen sold are summarized in Table 21. The operational cost of the refuelling stations have been assumed to be 4% of the annual capital expenditure (Ricardo, 2021) and the operational time is set at 20 years.

Table 21: Calculation parameters for infrastructure cost of hydrogen refuelling stations.

Parameter	Assumption
Station capacity	2,000 kg/day
Utilization rate	70%
Yearly hydrogen sales	511 ton/year
Depreciation period	20 years
OPEX (as % of CAPEX)	4%

For a hydrogen station with a capacity of 2,000 kg of hydrogen per day the average yearly additional energy cost has been estimated to be between 0.60 €/kg and 0.70 €/kg, as can be seen in Figure 23, using a linear depreciation.

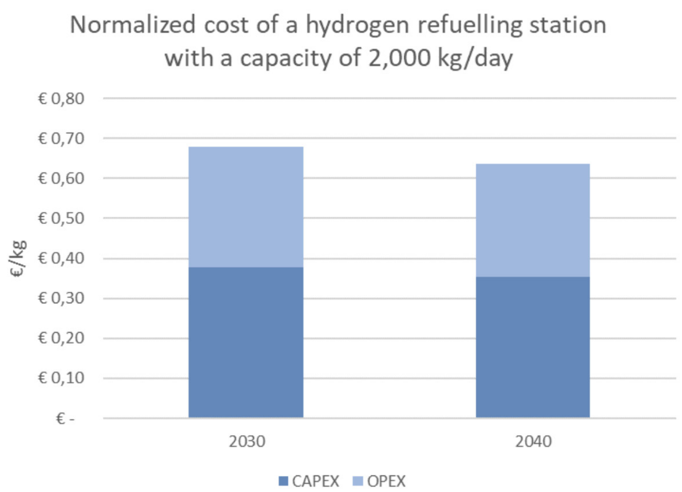

Figure 23: Investment cost and operational cost of a 2,000 kg/day hydrogen refuelling station.

5.2.5 Recharging infrastructure

The additional cost associated with private recharging infrastructure is considered in this section. Recharging at private depots is likely to be preferential for most applications. The benefit of recharging at depots (at night or during loading and unloading) is that the additional recharging time has minor impact on the daily logistical operations. The second benefit is that private charging is likely to be cheaper than public (fast) charging.

Figure 24 shows the relationship between chargers of various output powers and the cost of installation and operation per year. The equipment and installation costs are based on the AFIR impact assessment (Ricardo, 2021).

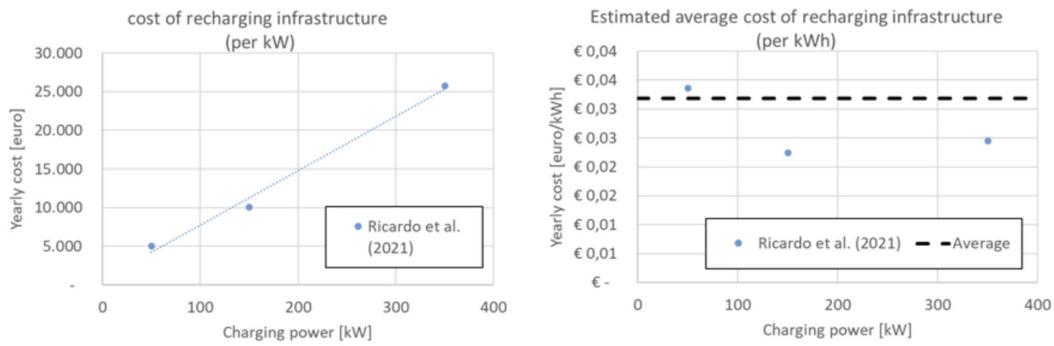

Figure 24: Relation between charging power and installation, operation, and material cost.

Given a certain utilization of the specific chargers, the average cost per kWh is computed. The overview can be found in Table 22. A high utilization of the charging infrastructure is beneficial for the overall average cost.

In this study a utilization rate of 35% is assumed (12 hours per day for 260 days per year on average) which results in 3,000 charging hours per year.

Table 22: Assumptions regarding charging infrastructure utilization.

		Charging power		
		50 kW	**150 kW**	**350 kW**
Utilization	hours/year	3,000	3,000	3,000
Energy	MWh/year	150	450	1050

To determine the average price per kWh of the various charging options, the annual cost (Figure 24 on the left) is divided by the yearly energy output of the charger. This method results in a cost estimation for private infrastructure between 0.02 and 0.04 €/kWh.

When charging at a depot also the recharging equipment cost must be accounted for. The costs for depot charging equipment are assumed to be 0.047 €/kWh based on (Kippelt & Burges, 2022) as a more conservative estimate.

Fast charging requires different type of equipment, resulting in different cost compared to depot charging. Based on (Kippelt & Burges, 2022), the costs for fast charging equipment are 0.073 €/kWh in 2020, 0.096 €/kWh in 2030 and 0.055 €/kWh from 2040 onwards. Moreover, the entity offering fast charging will in most cases be private companies. To account for profit and other potential cost, a mark-up factor of 10% is assumed on top of the charging equipment cost. These infrastructure costs are also used in (TNO, 2022).

The electricity cost for overnight charging is lower than the electricity price at public fast chargers (more expensive equipment, concession costs, profit margins). In the TCO analysis two different BEV tractor-trailers are analysed, one with a small battery and one with a large battery configuration. The truck with a smaller battery has a reduced CAPEX, but relies more on fast charging, leading to higher OPEX. In contrast, the truck with a larger battery is more costly to purchase but can reach a larger share of its operation on reduced electricity cost.

5.2.6 Resulting costs per unit of fuel / electricity

The fuel production costs are derived from the TNO study titled CHAIN. This study provides projections for production cost of e-diesel, e-methanol, e-DME, e-LNG and hydrogen for 2030. Diesel and electricity prices are based on (TNO, 2022).

An additional cost is added to account for the charging infrastructure, amounting to about 0.0475 €/kWh for depot charging and 0.055-0.096 €/kWh for fast charging.
The combined resulting energy costs are summarized in Table 23 for the year 2030. For the year 2020 the same prices are used for e-fuels (even though they do not exist). For hydrogen, a price of 10 euro per kg is used for the year 2020, as this is a typical price for hydrogen at existing refuelling stations.

Table 23: Energy cost projections summary in €/GJ - 2030.

Parameter	e-diesel €/kg	e-MeOH €/kg	e-DME €/kg	e-LNG €/kg	H_2 €/kg	Electricity	
						Depot	Public
Production and import	50	40	45	83	39	0.20	0.20
Last-mile distribution	0.5	1.1	0.9	1.0	7.9	-	-
Infrastructure	0.9	2.0	1.4	3.7	5.6	0.17	0.33
Total	**52**	**46**	**47**	**88**	**50** *(42-59)*	**37**	**53**

Table 24: Energy cost projections summary in €/kg (and €/kWh for electricity) – 2030.

Parameter	e-diesel €/kg	e-MeOH €/kg	e-DME €/kg	e-LNG €/kg	H_2 €/kg	Electricity (€/kWh)	
						Depot	Public
Production and import	2.13	0.87	1.28	4.47	4.75	0.08	0.08
Last-mile distribution	0.02	0.02	0.03	0.05	0.95	-	-
Infrastructure	0.04	0.04	0.04	0.20	0.67	0.05	0.10
Total	**2.20**	**0.93**	**1.35**	**4.72**	**6.4** *(5.3-7.4)*	**0.13**	**0.19**

5.2.7 Maintenance and Insurance

The expected maintenance costs and insurance rates are also adapted from a prior study (TNO, 2021b). As explained in the introduction of chapter 5, taxes have not been considered for this study.

Table 25: Yearly vehicle cost (TNO, 2021b).

Description	Units	ICEV	BEV	FCEV
Maintenance cost	€/year	7,000	3,500	5,250
Insurance	% of CAPEX	1.3%	1.3%	1.3%

Assumptions with respect to maintenance and insurance costs are summarized in Table 25. The BEVs have significantly fewer moving mechanical parts than ICEVs and therefore, require less maintenance. Therefore, the maintenance needed is restricted to other components, such as the tyres and brakes. Consequently, the BEVs are expected to be significantly cheaper to maintain than ICEVs. Given that FCEVs are more complex than BEVs and yet, have fewer mechanical parts than ICEVs, the maintenance cost is evaluated as the average of the costs for BEVs and ICEVs.

5.3 TCO results

In this section, the total cost of ownership is determined for the various combinations of drivetrains and energy carriers. This TCO calculation is performed for an annual vehicle mileages of 100,000 km/year.

The cost components and energy-uses that are included in this TCO calculations are the ones discussed in the previous sections. The schematic overview below shows how these cost components are used to determine the TCO.

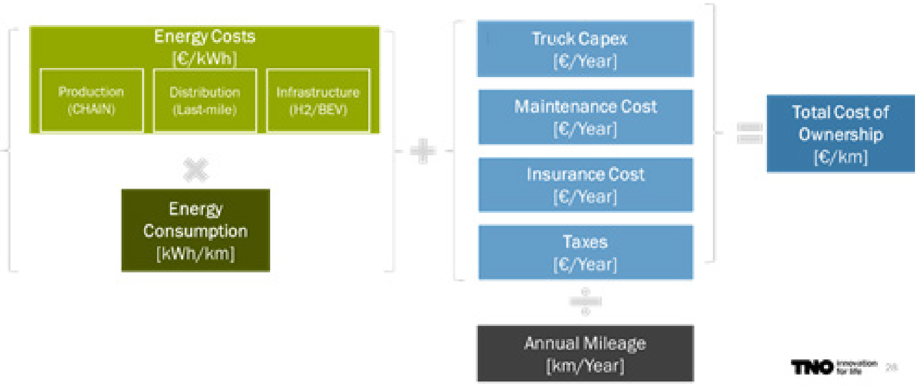

Figure 25: TCO model breakdown.

The annualized CAPEX cost of the vehicle is computed with the following parameters:
- Economic lifetime: 8 years
- Financing cost: 2.25%
- Residual value: 20%

The energy cost per kilometre used in the TCO model are given in Table 26. The diesel price used in this model is 0.49, 0.73 and 0.78 €/l (excluding VAT and excise duties) for the years 2020, 2030 and 2040. The corresponding depot charging electricity costs are 0.17 €/kWh, 0.17 €/kWh and 0.16 €/kWh, while those for public fast charging are 0.30 €/kWh, 0.30 €/kWh and 0.29 €/kWh.

Table 26: Energy cost values including distribution and infrastructure cost used in the TCO model.

Energy cost (€/km)[26]	**2020**	**2030**	**2040**
Diesel	0.21	0.18	0.17
e-diesel	*0.63**	0.51	0.51
e-Methanol	*0.59**	0.48	0.48
e-DME	*0.57**	0.46	0.46
e-LNG	*1.06**	0.87	0.87
H_2-ICE	1.01	0.59	0.59
BEV (400 kWh)[27]	0.17	0.16	0.15

26 This is calculated as the product of the specific energy consumption (kWh/km) and the specific cost of the energy source (€/kWh).

27 The electricity costs defined for the Battery-Electric Vehicles accounts for a weighted average mix of depot charging and fast charging. The vehicles are assumed to charge fully at the depot, and only the daily mileage exceeding the maximum usable range of the batteries is assumed to charge at the fast chargers.

Energy cost (€/km)[26]	2020	2030	2040
BEV (750 kWh)	0.16	0.14	0.14
H_2-FCEV	0.74	0.45	0.44

* It should be noted the 2020 costs for e-diesel, e-methanol, e-DME and e-LNG, are all based on 2030 energy cost values, since that is the earliest estimate for when they are expected reach an acceptable commercial readiness level. The differences with respect to 2030 cost values for these fuels are therefore restricted to improvements in efficiency. This implies that the 2020 results for the e-fuels powertrains are merely indicative and should be taken as such, since even if they were to be cost-competitive, they are not commercially available for large-scale public adoption.

5.3.1 TCO projections

In figure 26 to 28, the TCO results for 2020, 2030 and 2040 are presented. The TCO for the baseline diesel case increases, albeit marginally, over time due to an increase in the cost of the vehicle and fuel. ICE-trucks on e-fuels have comparable vehicle cost to fossil diesel trucks, but use a fuel with high production costs. They do not achieve a competitive TCO in the absence of suitable subsidies on the e-fuels or penalties (e.g., a CO_2-price) on the use of diesel.

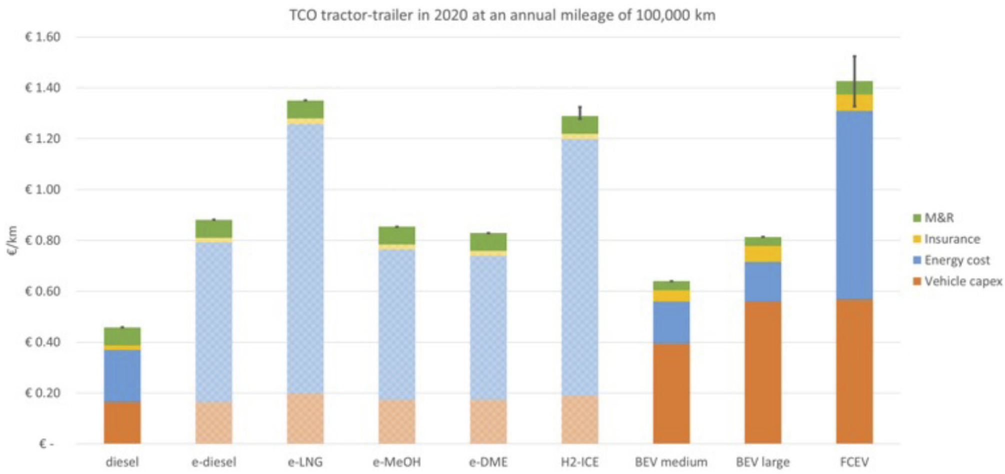

Figure 26: TCO comparison for different energy sources with an annual mileage of 100,000 kms in 2020.

By 2030, the costs for deploying a tractor trailer on (mainly) fossil diesel and battery electric trucks become similar if taxes are not taken into account. The significant cost reduction of BEVs is mainly due to the reduction of battery cost. The TCO of trucks on e-fuels and hydrogen is expected to be significantly higher.

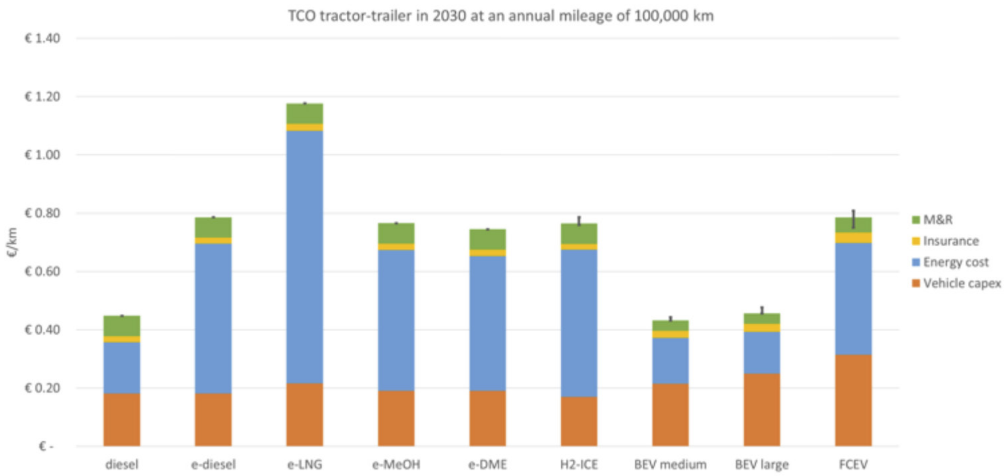

Figure 27: TCO comparison for different energy sources with an annual mileage of 100,000 kms – 2030 vehicle cost.

As explained in section 5.2.2, e-methanol is the only e-fuel for which production cost are available for 2040. Therefore, Figure 28 only shows values for conventional diesel, electric trucks, and e-methanol trucks for that year.

By that time, the TCO (excluding taxes) of the electric trucks is expected to drop below that of diesel trucks. The cost of trucks on e-methanol are expected to remain significantly higher. As trucks on e-methanol are amongst the lowest of the e-fuels assessed, it is likely that this will be similar for the other e-fuels.

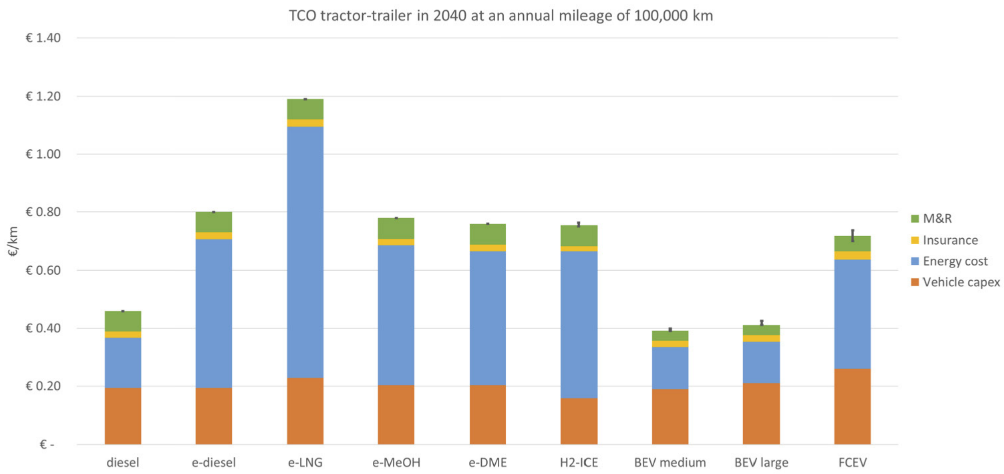

Figure 28: TCO comparison for different energy sources with an annual mileage of 100,000 kms – 2040 vehicle cost and mid projected energy cost.

In case hydrogen production cost would reduce to the levels mentioned in the literature sources included in Figure 18, hydrogen may become a cost competitive energy carrier. However, drawing more concrete conclusions would require a thorough hydrogen cost projection study based on the same methodology as used to derive production cost for 2030.

-06-
Safety

This chapter describes safety aspects related to using alternative fuels in long haul truck transport. It is not a complete analysis of all safety issues related to the use of e-fuels in this application, as that was not possible within the constraints of the project and not necessary given the exploratory scope of the study. A comprehensive evaluation of all relevant safety issues for the use of e-fuels requires a dedicated study in a different context. Instead, a choice was made for this project to provide a qualitative evaluation over a wide range of safety aspects related to e-fuels in trucks, based on available knowledge and expert judgement, and to augment this with a contribution to the improving the more in-depth understanding of a specific topic. Therefore, the focus of this chapter is on the risk to drivers and other road users near-by associated with traffic accidents leading to a rupture of the fuel tank.

Section 6.1 introduces the safety aspects of alternative fuels. The risk assessment related to traffic accidents is described in Section 6.2, while a discussion and conclusion are given in Section 6.3.

6.1 Safety aspects of alternative fuels

The use of synthetic diesel will involve similar safety hazards as conventional diesel. When alternative substances such as liquified natural gas (LNG), hydrogen or methanol are introduced as truck fuel, specific safety hazards are introduced as well. For LNG these are associated with flammability and the pressurised storage at cryogenic temperatures. For hydrogen, the hazards relate to flammability and storage at very high pressures (>350 bar)[28]. For methanol, the hazards are related to flammability (flash temperature lies at 10 °C compared to 56 °C for diesel oil) and toxicity.

There are two relevant aspects:
- Hazards related to the fuel properties;
- Effort needed to obtain equivalent safety.

The first aspect can be divided into the following categories:
1. Flammability;
2. Explosion hazard/uncontrolled failure;
3. Health risk.

The second aspect means that with sufficient (mitigating) measures the use of an alternative fuel, with different hazardous properties, could obtain the same safety level as e.g., diesel. Aspects related to the effort to obtain this are:
4. Containment system;
5. Handling equipment;
6. Required skills and knowledge;
7. Rescue and salvage.

28 Cryogenic storage of hydrogen in trucks is not foreseen in the near future.

So, categories 1 to 3 are related to the fuel properties, whereas aspects 4 to 7 are related to the effort needed for safe storage and usage of the fuels.

In a qualitative assessment the fuels are given a score on all 7 categories / aspects. The score is between 1 (low risk or low effort needed) and 5 (high risk or high effort needed). Categories 1 through 3 are taken almost directly from the safety data on the fuels based on NFPA 704 (NFPA 704, 2017). Aspects 4 through 7 are rated based on the information in the ADN (ADN, 2019) and ADR (ADR, 2019) documents.

As a second step the individual categories / aspects can be given weighting factors on how important they are deemed to be in determining the overall safety. In the analysis presented here, the weighting factors are assumed equal for all categories / aspects.

NFPA 704, published by the US National Fire Protection Agency (NFPA 704, 2017), describes dangers associated with hazardous substances. Four categories are distinguished:

- Flammability;
- Instability-reactivity;
- Health;
- Special notice.

It uses a 'fire or hazard diamond' with four boxes: red, blue, yellow and white (Figure 29).

Figure 29: NFPA hazard diamond (Example hydrogen)

The red box on the top indicates flammability of the substance, 0 indicates the substance will not burn, while 4 indicates that the substance is highly flammable. The blue box at the left-hand side indicates health hazards, 0 means there is no health hazard, while 4 indicates a high health hazard. The yellow box at the right-hand side indicates the instability/ reactivity of the substance, 0 means normally stable, 4 means readily capable of detonation or explosive decomposition. The white box at the bottom is used for the so-called special notice, it describes special hazards, e.g., oxidizing, simple asphyxiants, violent or explosive reaction with water.

The ADR (European Agreement Concerning the International Carriage of Dangerous Goods by Road) (ADR, 2019) issued by the UN Economic Commission for Europe), describes the mandatory regulations for transport of dangerous goods by road in Europe. It covers aspects such as construction and testing of containment systems, goods carrying conditions, loading, unloading, and handling. It also deals with vehicle crews, equipment, operation, and documentation.

The ADN (European Agreement Concerning the International Carriage of Dangerous Goods by Waterways) (ADN, 2019), also issued by the UN Economic Commission for Europe, describes the mandatory regulations for transport of dangerous goods by inland waterways in Europe. Its coverage is similar to the coverage of ADR. Both documents are issued by the United Nations Economic Commission Europe in Geneva.

ADR states requirements regarding carriage of dangerous goods which provide an indication of the required effort to do so in a sufficiently safe fashion. It distinguishes the following aspects:

- construction and testing of large packaging's, tanks, and bulk containers;
- equipment and operation;
- vehicle crews.

Additionally, it was decided to include rescue and salvage as a fourth aspect.

The following fuels / energy carriers[29] are considered in this section:

- Conventional fuels: diesel, petrol, LPG
- Natural gas: CNG, LNG
- Hydrogen: compressed, gaseous ($C\text{-}H_2$) and cryogenic, liquid ($L\text{-}H_2$)
- Methanol
- Ammonia
- Electric battery

The results of the qualitative assessment for the above-mentioned safety aspects are summarised in Table 27 and Table 28. Every aspect is scored between 1 and 5, where 1 means a low risk or low effort needed and 5 means a high risk or large effort needed.

Table 27:Safety aspects: fuel hazard characteristics.

	Safety aspect	Diesel	Petrol	LPG	CNG	LNG	C-H2	L-H2	Methanol	Ammonia	Battery
1	Flammability	3	4	5	5	5	5	5	4	2	1
2	Explosion hazard/ uncontrolled faillure	1	3	3	3	3	5	5	2	1	4
3	Health risk	3	2	2	2	4	1	4	2	4	3
	Total score	7	9	10	10	12	11	14	8	7	8

Table 28:Safety aspects: containment and handling.

	Safety aspect	Diesel	Petrol	LPG	CNG	LNG	C-H2	L-H2	Methanol	Ammonia	Battery
4	Containment system	1	1	3	4	3	5	2	3	4	1
5	Handling equipment	1	2	3	4	4	4	4	3	3	1
6	Required skill and know-how	1	1	2	3	4	3	4	1	2	1
7	Rescue and salvage	1	2	2	4	3	5	4	2	5	5
	Total score	4	6	10	15	14	17	14	9	14	8

Diesel is the first fuel in the tables, and it is also the fuel with the lowest risk. It is flammable but has a low explosion risk. The containment and handling can be safely done as it is stored under ambient conditions.

Petrol has the same storage conditions as diesel; however, it is more flammable than diesel and for this reason the handling equipment is slightly more elaborate, e.g., vapour-return-line.

Methanol is similar to petrol in storage conditions and handling. The higher score on containment system and handling equipment is due to the corrosive nature of methanol which requires special attention with regards to the used materials and spillage in case of a leak. As a fuel, however, methanol has a relatively low risk of explosion and poses low health risks resulting in a low score on its material properties.

All fuels discussed unto this point are stored under ambient conditions. The fuels to be discussed next require either elevated pressure, or low temperature to be stored efficiently. Both aspects will raise the effort needed in containment, handling, know-how and rescue.

29 Some of the fuels / energy carriers included here are not in scope for the other parts of this report.

LPG needs to be stored at low pressures, up to 11 bar, which raises the requirements for storage and handling. Additionally, it is more flammable than diesel and petrol. Overall, this results in higher risks and a higher score both from a material property point of view and from a safe usage point of view.

Natural gas is also highly flammable. It can be stored in two ways: liquid under cryogenic conditions (-162 °C) (LNG) or as a pressurised gas at ~250 bar (CNG). Due to the low storage temperatures required for LNG and corresponding risk of cryogenic burns, the health risks associated with LNG are higher than those for CNG. The low temperature (LNG) or high pressure (CNG) require more sophisticated storage and handling. Overall, this results in higher risks compared to conventional fuels and thus a higher score.

Similar conclusions as for natural gas can also be drawn for compressed (C-H_2) and liquid hydrogen (L-H_2). However, the corresponding storage temperature for liquid hydrogen is lower (-252 °C) and the corresponding storage pressure for compressed hydrogen is higher (350-700 bar). Furthermore, hydrogen has a very wide flammability range and is highly explosive. Consequently, the risks are higher, resulting in a higher overall score compared to natural gas.

Ammonia is stored at low pressures (10 bar). Furthermore, it is toxic and corrosive. This results in a higher health risk and additional requirements on storage and handling. One of the advantages of ammonia, however, is its low flammability and corresponding low risk of explosion under storage conditions. Consequently, ammonia poses a relatively low risk from a material property point of view, but a relatively large effort is required for safe usage.

Finally, for battery electric vehicles most factors result in low risk and low effort for safe usage. The two main concerns are the run-away reaction that is possible in some batteries and also the risks related to the presence of a voltage difference and possibly toxic fumes (in case of fire) in case of salvage and rescue.

In general, the use of alternative fuels poses higher risks than the use of diesel and petrol, from a fuel characteristics point of view. To ensure equivalent safety, proper containment and handling needs to be ensured and measures will be required to reduce the risk of dangerous failure. This can be achieved by either reducing the possible consequences of (a single) failure or reducing the likelihood of failure. Examples of measures that can be (and are) taken are introducing monitoring systems, system design following a safe life design approach, or a damage tolerant system. By implementing these measures, the risk associated with all fuels can be reduced significantly in an attempt to move from a yellow or red area in the risk matrix to (or near) the green area in the risk matrix.

6.2 Risk assessment related to traffic accidents

6.2.1 Risk approximation approach

This section zooms in on potential safety hazards of using fuel in a truck on the road related to fuel release as a consequence of traffic accidents. When considering this specific hazard, a schematic representation as shown in Figure 30 is helpful. The governing risk is expected to be ignition of released fuel. The diagram shows that the risk of ignition of the fuel consists of a few steps. First a traffic accident must occur (1st probability). Some accidents, but by far not all, will lead to release of fuel (2nd probability), e.g., due to tank rupture. After release, the fuel must catch fire or explode (3rd probability). This 3rd probability heavily depends on the fuel properties. These three probabilities determine the probability of fire or explosion following a traffic accident. On the other hand, there are the consequences of the ignited fuel. These are expressed in the effect distance. Combined with the number of persons in the affected area this yields the ultimate consequence, i.e., the number of people injured and/or killed.

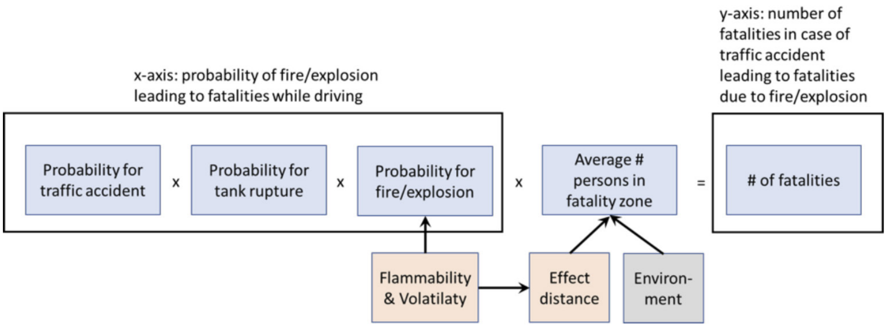

Figure 30: Schematic representation of risk. "x-axis" and "y-axis" refer to the risk matrix in Figure 31.

A common way to visualise risk is through the use of a risk matrix, as depicted in Figure 31. It depicts risk as a combination of the probability of occurrence of harm and the severity of that harm. In the context of fuels this harm is the release of the fuel followed by ignition causing a fire or an explosion, exposing bystanders to a heat flux or a pressure wave. In case of fuels stored at cryogenic temperatures there is the additional danger of frostbite.

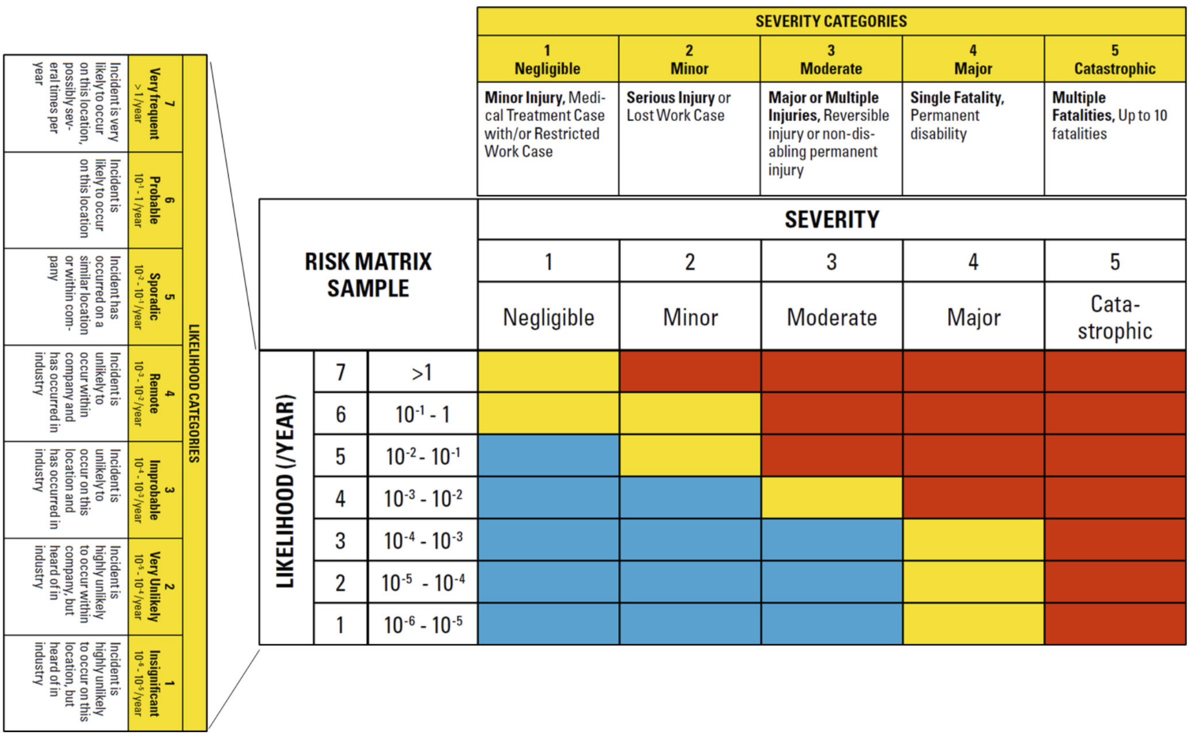

Figure 31: Typical risk matrix[30]

The final consequences are people losing their life or getting injured. The severity of such consequences can be categorised as indicated along the 'severity axis' of the risk matrix. The other part of the 'equation' is the probability or likelihood of the occurrence of harm. In the context of truck fuels these occurrences are events where fuel may escape and cause casualties in ways as described above. These occurrences

30 https://www.nen.nl/elektrotechniek/sil-platform

mostly concern trucks becoming involved in a collision or toppling over. The likelihood (probability) of such occurrences can be categorised as indicated along the 'likelihood axis' of the risk matrix.

Risk matrices come in many sizes and colours. The one used in this analysis is taken from the Dutch SIL Platform[29] . Severity (consequence) in the context of this report means number of people killed or injured in the incident. Likelihood means the yearly probability that the event will occur. It may be helpful to think of a yearly probability of say 10^{-4} (1/10000) in terms of one needs to bring 10,000 vehicles on the road to 'make sure' the event occurs (on average) once each year.

6.2.2 Consequences of loss of fuel containment

The current section describes the consequences part of the risk analysis. The analysis starts at the point that there is some loss of containment (LOC), i.e., part of the fuel is being released from the tank into the surroundings. This release can be instantaneous or continuous through a (small) hole in the tank. The LOC in itself is not the problem considered here[31], the effects it may have on the people in its vicinity are. Following the LOC of fuels several possibilities for harmful consequences following from their flammability exist: a pool fire, a jet fire, a Boiling Liquid Expanding Vapour explosion (BLEVE) or an explosion of the gas cloud. Each of these lead to different distances where the heat flux levels, or overpressure levels become harmful for people. Note that there is also the possibility that no fire or explosion will occur. The probabilities of each consequence depend on substance properties and surroundings. Other possible adverse effects are toxicity and asphyxiation, however, for fuels in an outside environment the effects mentioned earlier are most common.

Some examples of release scenarios for the carriage of dangerous goods via road, rail and water have been calculated by the Dutch 'Veiligheidsregio's'.[32] Possible scenarios following LOC of the cargo are given with the possible consequences. The results are effect distances for large quantities of substances. In addition, estimates are given for the failure probabilities of the cargo tanks. The scenarios for road transport of dangerous goods are used as an inspiration for the effect calculations for LOC of fuel described in the current chapter.

As an example, Figure 32 shows the possible consequence of the instantaneous release of methanol. Methanol forms a pool on the ground which gives a pool fire when ignited. Different effects on people and surrounding structures are shown. In the red circle the heat radiation results in lethality. In the orange circle people are affected and are unable to bring themselves to a safe place. The yellow circle depicts the area in which people can get themselves into safety. The surrounding buildings can be affected by fire, or heat radiation leading to fire or smoke.

31 But the spill may of course cause environmental damage.

32 https://www.scenarioboekev.nl

Figure 32: Schematic representation of pool fire, taken from [https://www.scenarioboekev.nl/].

For five fuels effect distances have been determined:
- diesel,
- petrol,
- methanol,
- LNG,
- and compressed H_2 at 500 bar.

The main consequence for diesel and petrol is a pool fire. This is also the case for methanol. For LNG pool fire is also an option, as is a BLEVE. For compressed H_2 it is either an explosion or a jet fire. For all fuels, the tank volume is kept constant at 2 m^3. This means that the amount of energy in the tank is different for each of the fuels, as the energy density differs per fuel. This is not in line with the vehicle configuration in the previous chapter, but the value of 2 m^3 is chosen for a relative comparison. The assumption of constant volume, however, is more or less in line with the dimensioning of trucks in chapter 5, taking account of the energy density of the energy carriers and volume limitations of the tractor configuration.

The calculations have been performed using EFFECTS v11.3 (GEXCON), which is a specialised software for this type of calculations. It is similar to safety-NL which is used in the Netherland to perform safety studies for industrial locations where hazardous chemicals are used.

Both overpressure and heat flux can lead to fatalities. For heat flux a value higher than 35 kW/m^2 leads to 100% lethality, a value of 10 kW/m^2 leads to 1% lethality. For overpressure, a value higher than 0.3 barg leads to 100% lethality and 0.2 barg leads to 1% lethality. In this study the distances at which 1% lethality is reached will be used to compare different fuels.

The first fuel to be discussed is diesel. As this is the most common truck fuel at the moment, it is used as a reference. For this fuel the effects of a pool fire following a total LOC have been calculated. The resulting effect distance for which 1% lethality occurs is 30 m.

The same calculation is performed for petrol and methanol. For these fuels an effect distance of 34 m is reached, which is slightly higher than for diesel.

Based on these numbers one could conclude that methanol is as safe as petrol. However, the probability for a pool of methanol to ignite is much larger than for a pool of petrol, due to the lower flash point of methanol. As this probability of ignition can't be taken into account looking only at effect distances, for a proper comparison of risk also probability needs to be taken into account.

Table 29: Overview of effect distances of pool fires

	Diesel	Petrol	Methanol	LNG
35 kW/m^2	16	17	23	51
10 kW/m^2	30	34	34	82

For LNG there are two possible scenarios to consider: pool fire and hot BLEVE. A pool fire results in a heat flux and a BLEVE results in both a heat flux and overpressure. For the pool fire 1% lethality is found at 82 m. An overview of all effect distances for pool fires is shown in Table 29.

The other possible effect for LNG is a BLEVE. A schematic representation of a BLEVE is given in Figure 33[33]. For the BLEVE the effect of the heat flux reaches farther than the effect of the overpressure: 49 m vs 13 m. A maximum heat flux of 10 kW/m^2 is reached at 123 m, however, due to the limited time frame for which the fire ball is present the distance to 1% lethality is smaller: 49 m. Of the two scenarios for LNG, the pool fire has the largest effect distance, and this value will be used for the comparison to the other fuels.

LNG Hot BLEVE	Effect distance (m)
0,35 barg	10
0,17 barg	13
10 kW/m^2 (Due to short time 1% lethality at 49m)	123

Figure 33: Results for LNG BLEVE.

For H_2 the scenarios for a jet fire and for an instantaneous release have been studied. The drawings in Figure 34 are taken from [https://www.scenarioboekev.nl/] and show the transport of H_2 in cylinders. For the case considered here it is assumed that the H_2 is stored in a single 2 m^2 tank.

For the jet fire the 1% lethality distance is 19 m, for the instantaneous release the effect distances are 36 m and 26 m for the overpressure and the heat flux, respectively. The largest distance found is 36 m, this value will be used for the comparison with the other fuels.

EFFECT DISTANCE - H_2 AT 500 BAR

H^2 - 500 bar Jet fire [kW/m^2]	Effect distance (m)
35	17
10	19
4	22

33 The drawing is taken from [https://www.scenarioboekev.nl/]

H^2 - 500 bar	Instanntaneous release		
Overpressure [barg]	**Effect distance (m)**	**Heat flux [kW/m²]**	**Effect distance (m)**
0.3	33	35	12
0.2	36	10	26
0.1	59	4	42

Figure 34: Results for H_2 jet fire (top) and H_2 explosion (bottom).

Table 30: Comparison of effect distances.

Fuel	Distance (1% lethality)	Scenario
Diesel	30	Pool fire
Petrol	34	Pool fire
Methanol	34	Pool fire
H_2 (500 bar)	36	Explosion
LNG	82	Pool fire

Table 30 shows the overview of the effect distances for different fuels. Petrol and methanol have the smallest distance and LNG results in the largest effect distance.

Diesel, petrol, and methanol are similar in storage conditions: liquid under ambient conditions. The main difference between these substances is not in the effect distance, but in the probability that the vapour above the pool will ignite following a release. Diesel will be very hard to ignite, whereas methanol is easily ignited.

Hydrogen is stored under very different conditions. It is a compressed gas at 350 – 700 bar (500 bar used as example in this assessment). The effect distance following an explosion is slightly larger than the distances for petrol and methanol.

The effect distance for LNG is by far the largest from the table. This is due to the LNG properties. It is stored below its boiling temperature. In case of LOC, the liquid LNG is released and forms a pool. However, due to the low boiling temperature, the pool will start to evaporate quickly. The result is much vapour that will burn and for that reason generates a high heat flux.

6.2.3 Indicative estimate of probabilities

The hazardous event is loss of containment, i.e. the fuel is spilled from its tank, possibly followed by ignition. Contrary to diesel, methanol, H_2 and LNG are susceptible to ignition because of either a low flashpoint or their gaseous nature. This event can occur when the fuel tank ruptures following a road accident such as a collision or a topple over. Within the time available for the investigation, it proved impossible to find statistics of road accidents where truck fuel is spilled. Fortunately, statistics on road accidents are available, which report on fatalities. A breach of the fuel tank of a truck, leading to a fuel spill, will mostly occur in severe accidents causing severe damage to the vehicle. Similarly, it is likely that the majority of fatalities among drivers or co-drivers of trucks and tractor-trailers occur in such type of severe accidents. It is therefore assumed that accidents with fatalities involving drivers or co-drivers of trucks and tractor-trailers are also a good estimate of the probability of loss of fuel. Although there is no evidence, it is expected that with this assumption results and conclusions regarding probabilities of accidental fuel losses will be conservative.

The Dutch institute for road safety research (SWOV) publishes the number of yearly fatalities in traffic for distinct traffic modes as well as the number of vehicles in operation, as shown in Table 31 and Table 32 respectively.

Table 31: Number of fatalities of occupants (driver + codriver in case of truck) and other persons involved in an accident with a vehicle of a specific category per 10^9 kms driven by vehicles of that category in the Netherlands (yearly average 2009-2018). Source: https://swov.nl/nl/factsheet/vracht-en-bestelautos

	fatality risk occupants [per 10^9 km]	fatality risk other involved parties [per 10^9 km]
Passenger car	2.1	1.4
Van	1.1	2.9
Trucks and tractor-trailers	0.9	10.4

Table 32: Number and mileage of trucks and tractors with semitrailers operational in the Netherlands. Sources: https://swov.nl/nl/factsheet/vracht-en-bestelautos and https://opendata.cbs.nl/statline/#/CBS/nl/dataset/80302ned/table?dl=46992

Vehicle type	Number of Dutch vehicles in January 2019	Number of kms driven by Dutch trucks in the Netherlands in 2018 (x 10^6)
Rigid truck	62,963	2,058
Tractor-trailer	80,078	4,523
Total (trucks)	143,041	6,581

From these tables it can be derived that the 2009-2018 yearly average fatalities drivers + co-drivers rigid trucks + tractors equals 0.9 per 10^9 km. The 2018 mileage of Dutch rigid trucks + tractors on Dutch roads equals 6581 10^6 km. Hence the average annual mileage of one truck on Dutch roads equals 6,581 10^6 / 143,041 = 46,008 km. With these figures the yearly average of fatalities of drivers + co-drivers of one rigid truck or tractor-trailer equals 0.9 / 10^9 x 46,008 = 4.1 10^{-7}.

This probability is used as a proxy for the probability of the loss of containment of diesel fuel as a result of a traffic accident.

6.2.4 Risk analysis

The probability from the previous section can be used to indicatively plot the probability and severity of accidents with loss of fuel containment in the risk matrix for trucks on diesel as well as on alternative fuels with higher ignition hazards. This is depicted in Figure 35. It is noted that in this risk matrix probabilities below 10^{-6} are added by the author for the sake of the argument.

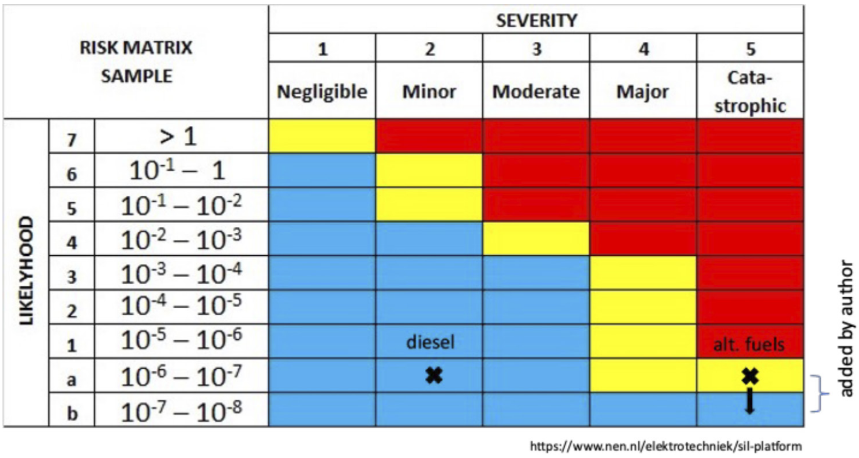

Figure 35: Risk matrix for trucks running on hazardous fuels

The locus on the right-hand side of Figure 35 indicates the risk for trucks running on hazardous fuels. The vertical position of the locus shows the yearly risk for one truck being involved in a fuel spilling accident. It is valid for a truck which is en-route. It does not include refuelling, being parked or (un) loading at a premises. The probability value of 4.1 10^{-7} is explained in the previous section. The severity 'value' (horizontal position of the locus) of 5 is based on a) the conservative assumption that for these alternative fuels a spill always leads to a fire or explosion and b) the observation that when an incident occurs effect distances around the spilling fuel tank are big enough to involve fellow road users in the vicinity of the truck.

Diesel is also indicated, see the locus on the left-hand side of the matrix. The probability of a fuel spill is assumed equal to that of alternative fuels; however the severity of the consequences is much less. This is mainly due to the high flashpoint of diesel. As a result, spilled diesel will not catch fire, in contrast with the significantly more flammable alternative fuels assessed in this study. For e-diesel the same conclusion applies as for conventional diesel.

Please note that the choice of the event 'fuel spill' determines the locus in the risk matrix. When the event 'fuel catching fire' would have been chosen, diesel would end up in the same severity category as the alternative fuels, but the likelihood category would be '10^{-7} – 10^{-8}' or even lower because of the low probability of diesel catching fire. Calculating the probability of ignition following a spill, could not be done within the scope of the project.

According to this risk matrix the application of fuels such as H_2, e-methanol and e-LNG would encourage further risk reduction measures to shift from the yellow area (ALARP) to the blue area (tolerable), as indicated by the arrow in the risk matrix. This can be done by strengthening the fuel tank or other measures reducing the risk of fuel spill in case of a traffic accident. For (e-)LNG such measures are intrinsically in place as the tank needs to be made of stainless steel and has to be double-walled for insulation purposes.

6.3 Discussion and conclusions regarding risk associated with loss of fuel containment

Table 30 lists effect distances, for methanol, hydrogen, and petrol of about 35 m and for LNG about 83 m. These are indicated in Figure 36 to assess the possible consequences in a highway setting. Assuming the fire or explosion does not occur immediately after the collision or toppling, a traffic jam will materialise behind the incident with the potential of involving fellow road users in the accident. In such a case potential lethalities can easily exceed 4 persons.

Figure 36: Effect distances

Hence, based on the SIL risks matrix, additional mitigating measures would be encouraged for methanol, LNG, and hydrogen as a fuel for trucks. It is noted that the chosen event is 'spill of fuel'. Moreover, it is also assumed that diesel will not ignite, neither does it develop a toxic hazard when spilled. Therefore, the effect distance of diesel is effectively zero in the risk assessment. As mentioned, the other approach is choosing as event 'fuel fire' but in that case an additional event would also need to be considered, i.e., 'development of toxic cloud.'

It is noted that the analysis reported here refers to risk to persons in the direct vicinity of the vehicle. Risk to the general public is not covered.

It should be stressed that the risk assessment with respect to probabilities and possible consequences of traffic accidents leading to loss of fuel containment presented here is indicative and based on a number of very rough assumptions. It is a mainly intended as a first attempt to illustrate how possible safety implications of the use of fuels other than diesel for trucks can be analysed and visualised. Whether the application of e-fuels, with fuel characteristics leading to a higher probability of ignition of spilled fuel, could lead to a net increase of the safety risks compared to diesel will highly depend on the availability and application of mitigating measures that can significantly reduce the probability of fuel spills.

For improvement of the assessment of the probability of fatalities associated with fuel catching fire or exploding after a loss of containment resulting from a traffic accident better insight is needed in the number of accidents with diesel vehicles in which loss of fuel containment occurs. For the alternative fuels more insight is needed in how the probability of tank rupture differs from that of diesel tanks in dependence of implementation of possible mitigation measures. Especially in case of hydrogen and LNG including crashworthiness of tanks should be considered because this property will substantially reduce the probability of loss of containment following a collision or toppling over. Also a better quantification of the probability of ignition for different fuels is needed to make a proper comparison with diesel possible.

Regarding the consequence analyses it is recommended to improve the estimation of effect distances through calibration of the analysis methods using results of dedicated tests.

The risk analyses also need to be extended with accident scenarios related to maintenance, fuelling, loading and unloading.

Regarding the risk assessment further work needs to be done on a suitable risk matrix, which should include criteria for larger numbers of fatalities (e.g., based on FN curves as used for external safety analyses).

Introducing the hazardous substances methanol, hydrogen, and LNG as fuels in trucks will obviously increase the number of tank transport movements of these substances. The acceptability of such an increase also needs to be investigated. It is noted that for The Netherlands it is prescribed how such an investigation needs to be conducted. Please refer to '*Handleiding Risicoanalyse Transport*' (https://www.rivm.nl/handleiding-risicoanalyse-transport-hart).

-07-
Applicability

Applicability in this context addresses the impact of alternative energy carriers on the operation of a logistical service provider.

7.1 Range and flexibility

One of the most noticeable differences between the various types of energy carriers is the range of a vehicle on a single tank or battery charge. The use of e-DME, e-methanol and e-LNG in ICE vehicles results in a lower range than the use of e-diesel due to their lower energy density. However, as the share of tractor-trailers driving more than 1000 km per day on average is very limited (see Figure 3), only one time refueling would be required for most trucks using e-DME, e-methanol, e-LNG, or e-diesel.

Hydrogen fuel cell vehicles currently have a significantly lower range than trucks running on e-fuels, but the hydrogen storage capacity is expected to increase to levels where a range of 1000 km would become possible. Hydrogen ICEVs will likely stay behind slightly due to their lower energy efficiency. A range of approximately 850 km is expected in time.

In general, battery electric vehicles have the lowest range of all energy carriers / drivetrains assessed. Even with optimistic battery capacity projections the range of battery electric vehicles will be lower than the alternative options, about 540 km on one fully charged large battery. Also, at a (very) high charging capacity of 1MW, recharging times of battery electric vehicles are longer than refueling times for the other energy carriers.

The table and corresponding figure below show the typical range of the vehicle given a certain tank volume / battery capacity. In addition, the recharging / refueling rate and the driving distance per hour of charging and refueling are other important metrics. E-diesel provides the end user with the most flexibility followed by other e-fuels and H_2. For H_2 this requires significant developments, though. Battery electric trucks provide the lowest deployment flexibility to the user.

*Table 33: Typical range, onboard energy capacity and refuelling characteristics of tractor trailers. * for battery electric trucks it is assumed that only 90% of battery capacity is usable.*

Energy carrier / drive train	Tank / battery capacity	Range [km]	Refueling / recharging rate	Range added per hour of refueling / recharging [km/h]
e-Diesel	400 - 600 liter	1500 - 2200	70 l/min	~15000
e-Methanol	400 - 600 liter	650 - 850	70 l/min	~6800
e-DME	400 - 600 liter	800 - 1000	70 l/min	~8200
e-LNG	300 kg	1000 - 1200	50 kg/min	~12000
H2-ICEV	40 kg	~420	3 kg/min	~1900
H2-ICEV	70 kg	~850	7 kg/min	~5100

Energy carrier / drive train	Tank / battery capacity	Range [km]	Refueling / recharging rate	Range added per hour of refueling / recharging [km/h]
FCEV (current)	40 kg	~530	3 kg/min	~2400
FCEV (expected)	70 kg	~1100	7 kg/min	~6700
BEV (current)	350 kWh	~220	350 kW	~220
BEV (expected up to)	950 kWh	~750	1000 kW	~780

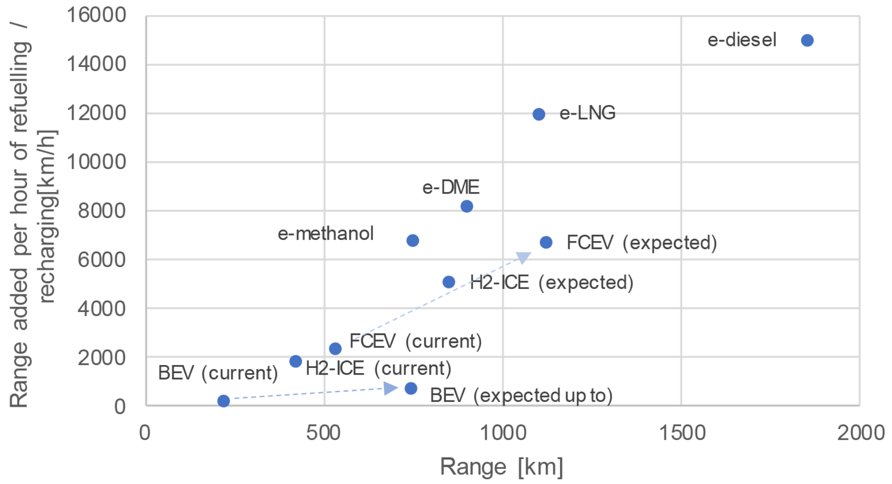

Figure 37: Range on a full tank or battery compared to range achieved per hour of refuelling / recharging.

The range of diesel trucks will remain greater than that of electric trucks, even when they are equipped with large batteries. In case the variation between days as found in section 2.4.2 is assumed to representative for the Dutch fleet in general, then approximately 40% of all tractor-trailers drive less than 580 km 95% of the days they are being deployed and would therefore require only overnight charging.

Currently there is no real incentive for logistical companies to deploy trucks in a similar way from day to day as all (diesel) trucks can have a similar large range. However, to prevent much high-cost opportunity charging or driving with oversized battery packs, it will become more important to match a trucks battery size and it trip lengths. In other words, have a truck with a battery size that is fit for purpose. In case the spread of day-to-day milage can be halved, approximately 65% of all tractor-trailers would drive less than 580 km 95% of the days they are being deployed. Including an half hour of opportunity charging at 550 kW, the daily range would increase with an additional 240 km to a total of almost 820 km per day. Depending on the possibility to optimise the logistic panning, for 85% to 95% of all tractor-trailers a battery electric truck would suffice.

Tractor-trailers that drive even more kilometers per day will require even more opportunity charging during the day. Figure 38 shows an example of a typical day for an electric long haul truck driving 1100 kilometers in one day. This requires close to 16 hours of driving and would require two drives due to the minimum requirements on maximum daily and weekly driving times, minimum breaks and daily and weekly rest periods (Regulation (EU) No 165/2014). In this example the assumed battery size is 665 kWh, the overnight charging power is 70kW, the opportunity charging power is 550 kW and it is assumed that 10% of the battery capacity cannot be used. In case chargers are used with significantly higher power levels less charging time would be required. In case of charging at 1000 kW (such chargers are being developed), the charging time would be 25 minutes instead of 45 minutes. With such chargers it becomes less crucial that a charger is available immediately available at arrival on the charging location.

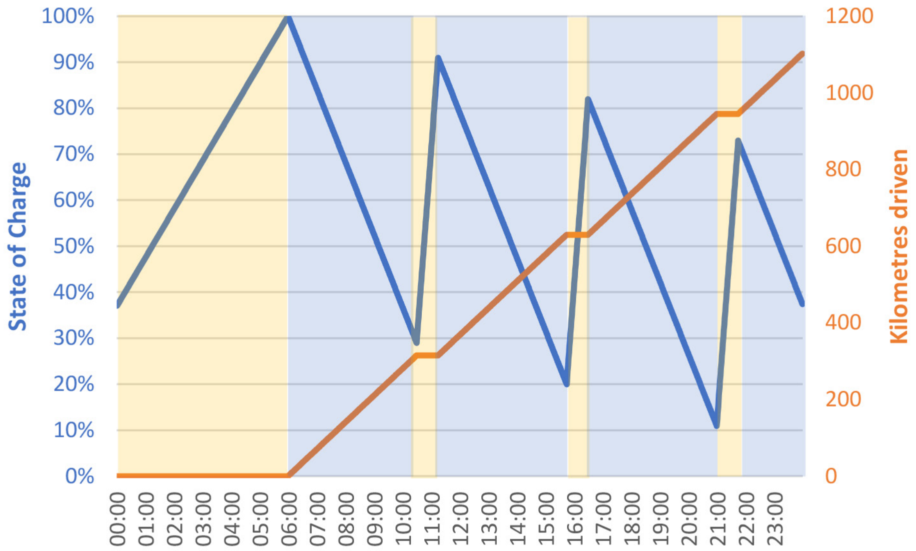

Figure 38: State of charge and kilometres driven of a typical long-haul truck with a (minimum) battery size of 665 kWh, overnight charging power of 70 kW and opportunity charging power of 550 kW (yellow is charging, blue is driving).

However, the fact that a certain battery size is sufficient for the average daily distance for a certain share of the trucks does not imply that the same share of vehicles can be electrified. If a specific truck drives a trip higher than its daily average, it requires more (public) fast-charging. To avoid (costly) waiting times at public fast-charging stations one or more trucks using alternative energy carriers with increased ranges can be included in the fleet for those specific trips. This does, however, introduce a certain sacrifice in flexibility, since not every truck can be used on every trip. Additionally, increasing complexity is added to the operation in terms of planning and optimization. Therefore, the uptake of electric trucks can fall behind the technological and commercial potential, since companies can prefer other options for other reasons than costs and range and may opt to wait for battery and truck prices to decrease further to buy cheaper trucks with larger batteries (and increased range).

Having multiple technologies can be an unwanted situation for fleet owners, especially in case of relatively small fleets, since it requires maintenance knowledge of various technologies. The uptake of electric vehicles by a certain company will initially be dependent on the possibility of overnight recharging at their private locations. Companies that rely on public charging or do not have reliable access to overnight chargers are likely to be reluctant towards a fast adoption of battery electric vehicles.

7.2 Available infrastructure

The introduction of new powertrain / energy carrier combinations is highly reliant on the available recharging or refueling infrastructure. Refueling or recharging infrastructure can be realized at private depots but that requires round-trips in the operation. Especially for long-haul transport to other European countries the possibility to recharge and refuel must be during the trip and/or at the destination location. Depending on the exact amount of battery electric vehicles and available infrastructure a certain central reservation system will have to be put in place to avoid unwanted waiting times.

In 2021, the European Union has put out a proposal for a new regulation addressing this precise issue, called AFIR (alternative fuel infrastructure regulation). In AFIR, the requirements for hydrogen refueling and electric recharging stations along the main European roads are described. The AFIR, however, does not address any regulations regarding e-fuels for vehicles with an internal combustion engine. A European intention for an overarching e-methanol or e-DME network is therefore not currently considered.

E-diesel is essentially a drop-in fuel for which the infrastructure is already in place. It therefore also provides the most flexibility as it can be used interchangeably with regular fossil diesel (if both pure fuels and/or the blends meet the engine specifications).

7.3 Other options than one on one replacement of vehicles

Besides one on one replacement of vehicles, there are other options to realize net zero emission heavy duty road transport. Such options would especially be relevant for vehicles with drivetrain types with a limited range, mainly battery electric trucks.

Some of the available options are

- Electric trucks with one additional swap of tractors: allowing one tractor to recharge while another drives on will require more trucks and therefore higher cost but does not require an additional infrastructure network.
- In motion charging of electric trucks: The issue of limited range is mainly with very long-distance trucks. Most of these drive significant distances over stretches of highways. Overhead wires and catenary systems may power electric trucks, limiting the required battery capacity and recharging times. Less recharging time would allow for longer distances in the same driving period. Lower battery costs are compensated for by higher infrastructure costs.
- Modal shift to inland shipping or trains: Especially the latter is in most cases already a zero-emission transport mode that can cover long distances.

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Commercial Readiness Level

The commercial readiness level (CRL) of alternative energy carriers and drivetrain types are a measure for the (short-term) market scale up potential. In other words, if a technology is not commercially ready at a certain point in time, it will not be possible to mass produce it at a for consumers acceptable cost level. It is therefore a proxy for the possibility for a technology to be mass deployed at that point in time. Since the required decarbonization of mobility is quite time sensitive, it is vital that technologies are commercially ready at the time that they are needed.

8.1 CRL of assessed energy carriers and drivetrain technologies

The commercial readiness of the various powertrain / energy carrier combinations is assessed on three different levels: the production of the energy carrier, the recharging / refueling infrastructure, and the vehicle technology. In the table below an overview of the current commercial readiness levels is provided.

Table 34: Commercial readiness of production, infrastructure, and vehicle technologies with respect to application in heavy duty road freight transport.

<table>
<tr><th>Type</th><th>CRL Production</th><th>CRL Infrastructure</th><th>CRL Vehicle</th></tr>
<tr><td>Electricity / BEV</td><td>Medium/High: Electricity is available but is still largely reliant of fossil sources.</td><td>Medium: For private regular chargers.

Low: For very fast public chargers. Especially the scale of infrastructure is too low.

Electricity grid needs to be upgraded.</td><td>Medium: Proven technology, yet still expensive. Already maturing for passenger cars and busses.</td></tr>
<tr><td>Hydrogen / FCEV</td><td rowspan="2">Medium: Fossil based hydrogen is widely available. Green hydrogen technology exists but at a small scale.</td><td rowspan="2">Low: Technology is being developed but not widespread for truck applications. Also, the refuelling speed needs to increase.

Distribution networks need to be established.</td><td>Medium: Proven technology yet still expensive.</td></tr>
<tr><td>Hydrogen / ICEV</td><td>Medium: Currently non-existent, but combustion technology is close to diesel drivetrain and expected to be available by 2025</td></tr>
</table>

Type	CRL Production	CRL Infrastructure	CRL Vehicle
e-diesel / ICE	**Low:** Not yet commercially available.	**High**: Diesel refuelling infra widely available throughout Europe.	**High**: If e-diesel is certified as a drop-in fuel.
e-LNG		**Medium**: Limited LNG infra available	**High**: If e-LNG is certified as a drop-in fuel.
e-methanol / ICE		**Low:** Non-existent	**Medium:** Currently non-existent, but technology close to diesel drivetrain
e-DME / ICE			

8.2 Synergy with other transport modes

Light duty vehicles are expected to make use of electricity as the main energy carrier. Therefore, battery electric drivetrains will be developed despite the superior technology of heavy duty vehicles. Moreover, electric infrastructure will have to be rolled out for light duty vehicles. Additionally other sectors are also expected to be using more electricity in the future. This is for instance the case in the built environment as well as in the industry. Besides mobility, these sectors will also drive the enforcement of the electricity grid.

The maritime and aviation sector will likely be using e-fuels or biofuels due to the requirements regarding energy density of the energy carriers. Therefore, these transport modes will drive the production of e-fuels and biofuels.

Since hydrogen is needed to produce e-fuels, the demand for e-fuels will also drive the production of hydrogen. Moreover, hydrogen will also play an important role in industrial processes that require high temperatures.

8.3 Conclusion

As can be concluded from the table, the CRL levels of the energy carriers, recharging / refuelling infrastructure and drivetrain technologies vary greatly. For the uptake of BEVs, the largest challenges are in the development of infrastructure and network capacity. At this moment no public recharging infrastructure is available at high enough power levels to quickly recharge truck batteries. Moreover there are only very little recharging points on private depots. In many cases, realising rechargers in these locations will require enforcements of the electricity grid and local smart solutions, such as smart charging and / or stationary local electricity storage. This is a significant challenge for the grid operators.

On the other hand, for e-diesel, the current refuelling infrastructure can be used, but there are no large-scale commercial production facilities yet and these are not expected for another decade. For the other e-fuels, the challenges regarding fuel production are similar to e-diesel, but additionally (limited) changes are required to the vehicles as well as the distribution infrastructure. For hydrogen use in trucks the commercial readiness of all three factors is relatively low. There is currently limited large-scale production of sustainable hydrogen (although fossil or blue hydrogen could be used during the transition to green hydrogen), the fuel cell technology is not yet mature and the amount of refuelling infrastructure usable for trucks is still limited.

Due to the expected uptake of battery electric light duty vehicles, the synergy with electricity is expected to be higher than for the other energy carriers. For hydrogen and e-fuels, other sectors will drive the production, but not the infrastructure. Although, of course infrastructure for certain e-fuels and biofuels is already widely available as it can be used in current infrastructure used for fossil fuels.

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Legislation

9.1 Introduction

At the European and Member State level there are currently various legislations, standards and policies in place that (may) affect the uptake in heavy duty road transport of the various drivetrain types and energy carriers assessed in this report. These can be aimed at different types of stakeholders (e.g., fuel suppliers, vehicle manufacturers, transport companies, or governments), affect either the supply of or the demand for vehicles and energy carriers, and may target different parts of the 'value chain', e.g., production, distribution (infrastructure) or use. Different policy instruments play different, and often complementary roles in the process of the transition towards sustainable road freight.

In this chapter an overview is provided of the relevant policy instruments and standards that affect the CO_2 emissions of heavy-duty road vehicles and the uptake of alternative propulsion technologies and energy carriers.

The policy instruments and standards discussed in this section are:

- Regulation No 85 of the Economic Commission for Europe of the United Nations (UN/ECE): Uniform provisions concerning the approval of internal combustion engines or electric drive trains intended for the propulsion of motor vehicles of categories M and N with regard to the measurement of net power and the maximum 30 minutes power of electric drive trains;
- Regulation No 49 of the Economic Commission for Europe of the United Nations (UN/ECE): Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines and positive ignition engines for use in vehicles;
- EN and ISO Fuel specification standards
- Regulation (EC) No 595/2009 of the European Parliament and of the council of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information and amending Regulation (EC) No 715/2007 and Directive 2007/46/EC and repealing Directives 80/1269/EEC, 2005/55/EC and 2005/78/EC;
- European CO_2 emissions standards for heavy-duty vehicles (EU) 2019/1242: obligates OEMs to market fuel efficient trucks and ZE alternatives;
- European Renewable Energy Directive 2018/2001/EU (REDII): obligates Member States and fuel suppliers to apply renewable fuels and improve the WTT performance of the fuel mix;
- European Fuel Quality Directive 2009/30/EC: obligates Member States and fuel suppliers to reduce the greenhouse gas intensities of fuels;
- European Alternative Fuel Infrastructure Directive 2014/94/EU: obligates Member States to support the transition to sustainable mobility by implementing a minimum required level of charging and alternative fueling infrastructure;
- European Weights and dimensions Directive 96/53/EC: specifying the weight and dimension limitations of trucks, busses and coaches including specific additional allowances for zero-emission trucks;
- Dutch national policy on low- and zero-emission zones: obligates heavy duty vehicle users to use zero-emission vehicles inside (certain) urban areas.

Besides these legislations there are several (non-binding) policies and mechanisms affecting the decarbonization of heavy-duty vehicles, e.g., the Dutch national climate agreement and CO_2 footprinting of logistics companies.

All these policies are subject to continuous improvement and amendments and therefore, the summary below can only describe the current situation.

9.2 Regulation No 85 and 49

Manufacturers are only allowed to sell vehicles in European Member States if these vehicles comply with European legislation with respect to, among other things, safety and emissions. Compliance with this legislation is checked by means of type approval testing. Test procedures, such as those described in Regulations No 85 and 49, need to cater for the different (propulsion) technologies applied in vehicles. The introduction of new energy carriers or propulsion systems generally requires amendments to existing type approval legislation and associated test procedures.

9.2.1 Description

Regulation No 85 of the Economic Commission contains provisions concerning the approval of internal combustion engines and electric drive trains used in light and heavy duty road vehicles. It describes the necessary tests for internal combustion engine vehicles and electric drivetrains and how the test results should be interpreted. This includes the test conditions, the data to be recorded, the required accuracy of measurements and the power correction factors.

Regulation No 49 of the Economic Commission deals with limiting the pollutant emissions from combustion engines as used in heavy duty road vehicles. This regulation describes:

- How to apply for approval (e.g., what information should be submitted by the OEM)
- What requirements should be met to receive approval
- What tests should be performed and how
- The way that vehicles should be prepared for the tests
- The conformity of production
- The conformity of in-service vehicles/engines
- Penalties for non-conformity of production.

This regulation also applies to the Euro VI emission standards as arranged under Regulation (EC) no 595/2009.

Part of the requirements for type approval testing of vehicles and engines concerns the definition of reference fuels, i.e. the specification of the properties of the fuels that are to be used for executing the test. In general the requirements for reference fuels are more specific than those for market fuels used in daily operation of the vehicles (see section 9.5).

9.2.2 Implications for different energy carriers

At the moment, these type of approval tests established in regulation 85 apply to combustion engines using leaded petrol, unleaded petrol, diesel oil, LPG, or natural gas and for (hybrid) electric powertrains. As long as e-diesel meets the NEN requirements EN590 and EN15940 it can be used in engines / vehicles type-approved for the use of conventional diesel. The same holds for e-LNG meeting relevant fuel specifications used in engines / vehicles approved for conventional LNG.

R85 does not yet contain specific provisions for testing combustion engines running on hydrogen. This means that hydrogen combustion engine vehicles cannot be type approved under the current legislation. This would also be the case for vehicles running on other alternative fuel types such as (e-)methanol.

Given that regulation 49 deals with tailpipe emissions, battery electric and fuel cell electric powertrains are not included in its scope. The combustion engine vehicles that either use diesel, petrol, LPG, natural gas (CNG / LNG), ethanol (ED95), ethanol (E85), or are dual fuel using a combination of these fuel types. As long as e-diesel meets the EN requirements EN590 or EN15940 and e-LNG complies with relevant fuel specifications, these fuels can be used in engines / vehicles type-approved for the use of the conventional variants. Other fuel types such as hydrogen and (e-)methanol are currently not included in the scope. Engines and vehicles on these fuels can therefore not be tested and therefore not be certified.

Actions are being taken to have more fuel types included in these two regulations. In 2020, an ACEA HD expert group on hydrogen combustion engine vehicles was established, which has defined the changes and amendments required for these two regulations to enable the type approval of hydrogen combustion engines. Due to COVID COM activities were postponed, but in September 2021 these were resumed.

9.3 Renewable Energy Directive (REDII)

9.3.1 Description

The Renewable Energy Directive, Directive (EU) 2018/2001[34], including its amendments, sets out a binding overall Union target for the share of renewable energies in the total energy consumption. This shall exceed 32% by 2030. In 2023, the European Commission will assess the technological state-of-the-art and the costs of renewable energy and will submit a proposal to increase the target share for 2030 if feasible. The member states are obliged to develop measures to contribute to meeting the 2030 target in their integrated national energy and climate plans[35]. REDII also sets out baseline shares of renewable energies for every Member State which must be met from 2021 onwards. To avoid ambiguities, REDII describes the calculation procedure that shall be used to determine these shares of energy from renewable resources. It is also possible – within certain limits – to transfer consumed energy from renewable sources from one Member State to another. By this means, overachievement of one Member State can be utilized to balance a delay in the energy transition of another country.
To reach the targets several provisions are set out in REDII. The Commission shall utilize financial instruments to facilitate the transition from fossil to renewable energy and support high ambitions of Member States. Furthermore, support schemes for renewable energies that can be applied by Member States are described. Support can, for example, include financial incentives or exemptions from tendering procedures (small projects and demonstrators only). Due to the highly integrated market of electricity and grid, joint projects, and support schemes of two or more Member States or Members States and third countries are incentivized by the Commission.

The transport sector is an important aspect of the transition to energy from renewable sources. REDII aims to streamline the energy transition in this sector. By 2030 at least 14% of the final energy consumption of the transport sector shall originate from renewable sources. The calculation method is also detailed in REDII. Biofuels, bioliquids, biomass fuels, e-fuels and recycled carbon fuels, contribute to

34 (Directive (EU) 2018/2001 of the European Parliament and the Council of the European Union of 11 December 2018 on the promotion of the use of energy from renewable sources)

35 Dutch Integrated Energy and Climate Plan: (The Nehterlands: Integrated National Energy and Climate Plan 2021-2030, 2019)

these targets provided that they fulfill certain sustainability and greenhouse gas emissions saving. For the biomass derived fuels, criteria are prescribed in Article 29 of Directive (EU) 2018/2001[34]. Verification and calculations related to these criteria are regulated in Articles 30, 31 and ANNEXES V, VI. For the use of e-fuels it is demanded that the greenhouse gas emissions savings are at least 70 % from 1 January 2021.

Similar to the overall Union target, the Commission will assess the progress in 2023 and increase the target share for the transport sector if feasible.

Member states are obliged to take measures to make energy from renewable sources available. This includes the refueling and recharging infrastructure as set out in their national policy frameworks[36].

To avoid that food and feed crops are used to produce biofuels and therefore the production of energy from renewable sources has a negative impact on the food market, additional provisions are set out in REDII. The share of fuels made from food and feed crops in the total energy consumption of the transport sector shall not increase by more than one percentage point compared to 2020. If the value in 2020 is below 1%, it may be increased by two percentage points. The maximum share is limited to 7%.

9.3.2 Implications for different energy carriers

REDII includes an overall renewable energy target of 14% by 2030 for the transport sector. The renewable sources that can be used to meet this target include renewable electricity and hydrogen as well as biomass derived fuels, e-fuels and fuels based on recycled carbon as long as they meet the criteria set in the directive. In that sense, the REDII incentivizes the use of renewable equivalents of fossil fuels, including hydrogen and e-fuels.

While the REDII includes specific sub-targets for certain fuels such as advanced biofuels, it does not include such sub-targets for hydrogen or e-fuels. However, the proposal for the revision of the REDII (the REDIII) does include such sub-targets, i.e., that 2.6% of the energy supplied to the transport sector should be met by e-fuels or hydrogen by 2030. Whether or not the incentives in the REDII and in the proposal for the REDIII are strong enough to achieve EU decarbonization goals requires an elaborate study and is therefore outside the scope of this project.

9.4 Fuel Quality Directive

9.4.1 Description

Directive 98/70/EC[37] and the Fuel Quality Directive, Directive 2009/30/EC[38], including their amendments, regulate the environmental quality requirements for petrol and diesel fuels in the European Union. Besides technical fuel specifications the Fuel Quality Directive also sets a requirement for the reduction of the greenhouse gas intensity of transport fuels by at least 6% by the end of 2020. To achieve this goal, a reduction of the life cycle greenhouse gas emissions of fuels is strived for. As is done in REDII, it is pointed out that the production of biofuels needs to be sustainable and that adverse effects on food

36 Dutch policy framework: (The Netherlands: Policy framework for the alternative fuels , 2016)

37 (Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC)

38 (Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions [...])

production and biodiverse lands shall be minimized. The impact of the conversion of biodiverse land into agricultural areas needs to be considered when assessing the greenhouse gas emissions of biofuels.

9.4.2 Implications for different energy carriers

As stated, FQD required a reduction of the GHG intensity of transport fuels of 6% by 2020. This GHG intensity is based on the life cycle GHG emissions, covering emissions from extraction, processing and distribution of fuels used in road transport. The emission reductions are calculated against a 2010 baseline. The emission intensity can be reduced via:

- The use of biofuels, electricity, less carbon intensive fossil fuels, and renewable fuels of non-biological origin (such as e-fuels),
- A reduction of upstream emissions (i.e., flaring and venting) at the extraction stage of fossil feedstocks.

The calculation method for the GHG intensity of different energy carriers, including electricity, biofuels, and e-fuels, plays an important role in meeting the emission intensity reduction target. The recommendations listed below are included in calculating the GHG intensity of different energy carriers:

- Electricity consumed by electric vehicles and motorcycles: Member States should calculate national average life cycle default values in accordance with appropriate International Standards. Alternatively, Member States may permit their suppliers to establish greenhouse gas intensity values (gCO_2eq/MJ) for electricity from data reported by Member States.
- Fuels from non-biological origin: Greenhouse gas intensities of several fuels, including fossil fuels and compressed hydrogen via electrolysis fully powered by non-biological renewable energy, are presented in a list. Average life cycle GHG intensity of electrolysis using renewable electricity is mentioned as 9.1 g CO_2eq/MJ.

9.5 EN and ISO fuel standards

9.5.1 Description

In order for fuels to be allowed for sale the European Union and several other European countries they must comply with EN fuel standards, which specify requirements with respect to a wide number of physical properties of the fuels. Compliance with EN fuel standards guarantees compatibility with engines developed for fuels meeting these standards. Different standards may exist for different applications, such as road vehicles or ships. In addition to European EN standards also national standards (such as the Dutch NEN) exist as well as global ISO standards.

For diesel the EN 590 standard applies. Subsequent adaptations of the standard have been used as policy instrument to lower the sulphur content of diesel. This standard also specifies the maximum amount of fatty acid methyl ester (FAME / biodiesel) that is allowed to be blended into conventional diesel (currently 7%). At the same time EN 14214 describes the requirements and test methods for pure FAME.

Fuels that comply with the EN590 standard can be used in all diesel engines. The engines have been developed and tested for the use of these fuels. The use of certain fuels, woth specs outside the bandwidths specified by EN590, can potentially lead to accelerated wear and tear and additional engine maintenance, e.g. dus to lubricating oil aging and fouling of fuel/lubricating oil filters. Truck diesel engines built before 2013 (Euro V and below) are usually released for higher biodiesel blends than the 7% maximum set by EN590. Modern engines (Euro VI) have more advanced injection systems, engine controls and emission control systems, so these vehicles cannot automatically handle fuels outside the EN590 standard. For the use of such fuels a separate type approval test is required. The extent to which engines are approved for the use of alternatives to regular diesel can usually be found out from the vehicle manufacturer or supplier.

Paraffinic diesel fuels such as HVO and certain types of synthetic diesel (e.g. GTL) are not able to meet some of the demands for physical characteristics set in EN 590. For these fuels a separate EN 15940 standard has been introduced.

The physical properties for hydrogen as a fuel for fuel cell vehicles are defined by the global ISO 14687:2019 standard. An EN standard is not yet available. The ISO standard among other things defines the strict limits for the allowed share of various impurities in the hydrogen. The catalyst in fuel cells is very sensitive to these impurities. ISO 14687:2019 defines different grades of hydrogen purity. Grade A, with the least stringent purity requirements, is suggested for use in combustion engines. For PEM fuel cells grade D is suggested. It is most likely that in the future only one single hydrogen fuel quality will be available at refueling stations. Since fuel cells require a higher purity than hydrogen combustion engines, it is likely that only high quality hydrogen will be available. As higher quality leads to higher production cost, the hydrogen will be more expensive than what would be required for hydrogen combustion engine vehicles.

ISO 16861:2015 specifies the characteristics of DME used as fuel, of which the main component is dimethyl ether synthesized from any organic raw materials. It is also applicable for DME used as replacement for diesel fuel. As e-fuels are not produced from organic raw materials, this standard does not apply to e-DME.

Fuel quality specifications for the use of 100% methanol in road vehicles in the EU have not yet been standardised. Under the Fuel Quality Directive (see section 9.4) and the EN 228 standard a maximum of 3 vol-% methanol is allowed to be blended in with petrol.

9.5.2 Implications for different energy carriers

EN fuel quality standards are an important instrument for assuring the compatibility of engines and the fuels applied in these engines. The end-user may expect problem-free operation of his vehicle, when a fuel meeting a specific standard is used in an engine that has been developed to be compatible with fuels having properties within the bandwidths specified by that standard. For an alternative fuel to be applied at large scale the existence of a specific EN of ISO fuel quality standard is therefore essential. If a future e-diesel meets the requirements of EN 590 or EN 15940, it can safely be used in existing and new vehicles with conventional diesel engines.

Fuel quality requirements are available for the alternative fuels assessed in this study that have the highest chance of being used in road transport, i.e. e-diesel and hydrogen. However, for (e-)methanol, e-DME and e-LNG fuel standards are not available, limiting the use of such fuels in road transport. Due the absence of plans for the large scale uptake of such fuels in road transport setting standards for these alternatives has not been a priority. Some level of deployment and first market formation, however, is generally necessary to accellerate further development of technologies for the production and use of these fuel, as well as to promote cost reduction and to gain experience with their practical use. Therefore defining appropriate fuel standards for these alternatives may be necessary to gain more practical experience with the role that these fuel may play in decarbonizing heavy duty road transport.

9.6 Alternative Fuel Infrastructure Directive / Regulation

9.6.1 Description

Directive 2014/94/EU[39], also referred to as Alternative Fuel Infrastructure Directive (AFID), defines a framework for building infrastructure for alternative energy carriers in the European Union. Such infrastructure is required to facilitate the uptake of vehicles with drivetrains that require these energy carriers.

The scope of the currently active directive covers, amongst others, recharging points for battery electric vehicles and refueling stations for LNG, CNG and hydrogen. According to the directive, Member States should have realized an appropriate number of publicly accessible recharging stations in densely populated areas by the end of 2020. By 31 December 2025 this should also be the case for LNG refueling stations along the most important European motorways (TEN-T network) to facilitate the operation of LNG-powered HD vehicles throughout the European Union. Member states have the option to establish hydrogen stations.

In July 2021 a proposal was published for a revision of the AFID[40,41]. In this document it is proposed to change this directive to a regulation (AFIR). It is motivated by an ex-post evaluation of Directive 2014/94 by the European Commission which found that Directive 2014/94 was "not well-adapted to the purpose of serving the increased climate ambition for 2030"[42].

Regarding heavy duty road transport, the proposal has a strong focus on the build-up of infrastructure for electricity and hydrogen along the TEN-T network. Whereas the demands in the existing AFID are defined qualitatively ("an appropriate amount"), the AFIR-proposal is more specific for electricity and hydrogen infrastructure and includes quantitative obligations for these energy carriers. Similar to the existing AFID, the AFIR proposal still requires member states to build up an appropriate number of LNG refueling stations for heavy duty road transport.

9.6.2 Implications on different energy carriers

For heavy duty vehicles specifically, the focus of the existing AFID is on LNG and to a lower extent hydrogen (as it is optional) and electricity (as it is only demanded in densely populated areas). In contrast, the newer AFIR proposal focuses mostly on electricity and hydrogen and to a lower extent on LNG (only qualitative obligations). It does not require member states to have infrastructure for e-fuels (nor biofuels) available. In other words, the proposal should ensure that vehicles depending on electricity or hydrogen will be able to move though the EU freely, while this is not arranged for the other energy carriers through this policy. On the other hand, e-fuels can be supplied by the same infrastructure as their fossil equivalents without (much) adaptations.

39 (Directive 2014/94/EU of The European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure, 2014)

40 (Proposal for a Directive of the European Parliament and The Council amending Directive (EU) 2018/2001 [...], 2021)

41 (Proposal for a Directive of the European Parliament and The Council amending Directive (EU) 2018/2001 [...] – Annexes, 2021)

42 (Commission Staff Working Document: Evaluation of Directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels infrastructure [...])

9.7 Weights and dimensions Directive

9.7.1 Description

The weight and dimensions of heavy-duty vehicles, buses and coaches within the EU must be within certain limits described in the weights and dimensions directive (EU) 2015/719. The objective of this directive is to improve road safety and to avoid damaging of roads, bridges, and tunnels. The directive also ensures that Member States cannot restrict the circulation of vehicles that comply with these limits. The Directive furthermore avoids national operators benefiting from undue advantages over their international competitors.

The directive grants derogations in terms of the length for trucks with improved aerodynamics. This also provides the opportunity to make them safer by including new features in the extra space in the driver cabin. Derogations on weights are also allowed for vehicles powered by alternative fuels. In 2019 an amendment was made to the directive[43], stating that the maximum authorised weights of vehicle combinations including alternatively fuelled or zero-emission vehicles shall be increased by the additional weight of the alternative fuel or zero-emission technology with a maximum of 1 tonne and 2 tonnes, respectively.

9.7.1 Implications on different energy carriers

Due to the 2019 amendment of the weight and dimensions directive mentioned above, zero emission heavy duty vehicles have a two tons higher weight allowance than the ones using fossil fuels. Based on the definition of 'alternative fuels' provided in the Alternative Fuels Infrastructure Directive, LNG, biofuels, and e-fuels are all included and would therefore have an additional weight allowance of 1 tonne.

9.8 CO_2 legislation for Heavy Duty Vehicles

9.8.1 Description

As part of its efforts to achieve the goals of the Paris Agreement, the European Union has implemented legislative measures to reduce the emission of CO_2 by Heavy Duty (HD) vehicles. Type approval – including emissions testing – of vehicles and engines for heavy-duty applications is regulated by Regulation (EC) No 595/2009[44]. Procedures with respect to the determination of the tailpipe emission of carbon dioxide are implemented by Commission Regulation (EU) 2017/2400[45]. In contrast to passenger cars, for which the CO_2 emissions for type approval are determined by testing a vehicle on a chassis dyno, the simulation software VECTO[46] is used to determine a "whole-vehicle" CO_2 emission value for HD vehicles. As inputs the VECTO tool uses specifications of the simulated vehicle configuration and data derived from standardized testing of the engine and various other components. Both regulations have been amended several times and are subject to continuous assessment and improvement. Commission Regulation (EU) 2019/318[47], for example, adapted the procedures for determination of CO_2 emission and fuel consump-

43 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R1242&from=EN

44 (Regulation (EC) 595/2009 of the European Parliament and of the Council of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and amending [...])

45 (Commission Regulation (EU) 2017/2400 of 12 December 2017 implementing Regulation (EC) No 595/2009 of the European Parliament and of the Council as regards the determination of the CO2 emissions and fuel consumption of heavy-duty vehicles [...])

46 Vehicle Energy Consumption calculation TOol - VECTO (europa.eu)

47 (Commission Regulation (EU) 2019/318 of 19 February 2019 amending Regulation (EU) 2017/2400 and Directive 2007/46/EC of the European Parliament and of the Council as regards the determination of the CO2 emissions and

tion. Monitoring and reporting of CO_2 emissions from new HD vehicles is detailed in another legislative act, Regulation (EU) 2018/956[48].

An important step towards a significant reduction of CO_2 emission by the road transport sector has been taken with Regulation (EU) 2019/1242[49] which sets emission performance standards for new HD vehicles, based on the metric as defined for determination and monitoring of the tailpipe CO_2 emissions from HD vehicles. These standards are intended as drivers for further developments to reduce fuel consumption – and hence emission of CO_2 – and of alternative, low and zero CO_2 emission technologies. According to Regulation (EU) 2019/1242 the specific CO_2 emissions of HD vehicles shall be reduced compared to the 2019/2020 reference values by:

- by 15 % from 2025 onwards;
- by 30 % from 2030 onwards.

Manufacturers can achieve this by reducing the CO_2 emissions of trucks on carbon-based fuels or by selling zero-emission trucks.

The 2030 target will be assessed in 2022 as part of the review of the Regulation. A possible revision of the target level may also be evaluated in the light of the strengthened overall GHG reduction targets as part of the European Green Deal and the Fit-for-55 package.

The HDV CO_2 standards apply to new vehicle sales and only for the four most common HD vehicle categories. These categories together produce the great majority of all kilometers driven and all CO_2 emitted by HD vehicles within the EU. A revision has been planned to broaden the scope in future amendments in order to cover a larger number of HD vehicle categories and buses.

For every reporting period from 2020 onwards, the European Commission determines the average specific CO_2 emissions in g/tkm of a HD vehicle manufacturer. The calculation is based on the data obtained from the CO_2 monitoring and reporting according to Regulation (EU) 2018/956[48]. To incentivize the deployment of

- zero-emission HD vehicles (< 1 g CO_2/kWh or < 1 g CO_2/km); and
- low-emission HD vehicles (specific CO_2 emissions less than half of the reference CO_2 emissions of its sub-group in 2019)[50];

a "zero- and low-emission factor" is taken into account. In their contribution towards achieving the target, the numbers of these vehicles produced by a manufacturer can be counted several times. In the reporting periods 2019 to 2024, zero-emission vehicles may be counted twice, and the number of low-emission vehicles may be multiplied by a factor depending on their actual CO_2 emissions. For the reporting periods from 2025 on, the zero- and low-emission factor is to be determined based on a 2 % benchmark. The exact procedure is detailed in Annex I of the regulation. The factor is limited to a maximum reduction of a manufacturer's specific CO_2 emission of 3 %. A further incentive of the application of zero-emission technologies is provided by the provision that sales of ZE-vehicles in categories other than the four

fuel consumption of heavy duty vehicles)

48 (Regulation (EU) 2018/956 of the European Parliament and of the Council of 28 June 2018 on the monitoring and reporting of CO 2 emissions from and fuel consumption of new heavy-duty vehicles)

49 (Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO 2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 [...])

50 Remarkably, there are no additional limitations on, for example, NO_x, CO or particulate matter. As a consequence, internal combustion engines fuelled with LNG or hydrogen can be taken into account without any further restrictions.

categories now covered by the CO_2 standard, also contribute to meeting the target applied to the four regulated categories.

Every year, the Commission sets and publishes a specific CO_2 emission target for each manufacturer. The value is the sum of the items below over all vehicle groups:

- the 15 % or the 30 % reduction target, respectively;
- the reference CO_2 emissions;
- the share of vehicles in every sub-group;
- the default mileage and payload factors applied for every sub-group.

The procedure is detailed in Annex I of the regulation. To win some flexibility, manufacturers are under certain conditions allowed to carry over emission debts and credits from a reporting period to the following one. If a manufacturer is found to exceed his limit, this fact is made public by the European Commission and an excess CO_2 permission premium is charged. The amount is determined based on the excess.

Furthermore, Regulation (EU) 2019/1242[58] sets provisions for the verification of monitoring data, the publication of information related to its scope, the evaluation of CO_2 emissions under real-driving conditions and in-service verification.

The targets, achievements and debts/credits of the average specific CO_2 emissions as well as the zero-/low-emission factors of the reporting period 2020 have been published by the commission in Commission Implementing Decision (EU) 2021/781[51].

9.8.2 Implications on different energy carriers

The following types of measures can be implemented by OEMs in order to reach the target:

- technical measures, applied to the truck / tractor, reducing the energy demand of the vehicle;
- technical measures improving the energy efficiency of ICE-based powertrains, incl. powertrain hybridization;
- dedicated engines for running on alternative fuels with low tank-to-wheel CO_2 emissions as a result of a lower C/H ration of the fuel, such as methane (LNG), methanol and hydrogen;
- battery-electric and plug-in hybrid-electric propulsion;
- fuel cell electric propulsion.

Since the targets are based on tailpipe CO_2 emissions, the use of carbon-based fuels with low well-to-wheel emissions, such as biofuels and e-fuels, is not rewarded by this directive. On the other hand, electric and hydrogen-fuelled vehicles count as zero emission under this legislation, regardless of the origin of the energy.

The target levels set for 2025 and 2030 by Regulation (EU) 2019/1242 are based on a techno-economic assessment and subsequent political validation of the feasibility, costs and potential for developing, applying and marketing the above mentioned technical measures in the period up to the target date. As such the application of biofuels and e-fuels in existing and newly sold ICE-based vehicles is to be considered as an alternative CO_2 reduction potential, that complements the contribution of the HD CO_2 regulation towards meeting the EU-wide climate objectives.

As mentioned in section 9.3, the application of fuels and other energy carriers with low well-to-wheel GHG emissions, including biofuels, e-fuels, electricity and hydrogen, is promoted by the Renewable Energy Directive. Targeted stakeholders for this Directive are the Member States, which are obliged to implement

51 (EU, 2019)

measures at the national level that contribute to meeting the targets set by the RED. Targeted stakeholders for these national measures are primarily the energy supply sector (production and distribution) and the end-users (vehicle and fleet-owners). However, to enable the use of alternative, more sustainable energy carriers, OEMs generally need to make various adaptations to the vehicles they produce. As far as electric, hydrogen-fuelled and natural gas vehicles are concerned, these efforts also contribute to meeting the OEM's target under the HDV CO_2 regulation. Vehicle adaptations required to enable the use of specific biofuels or e-fuels, however, are not rewarded by the HDV CO_2 regulation. As a consequence OEMs do not have a direct incentive to invest in these technologies. Incentives for such investments only indirectly derive from market demand for such vehicles, articulated by end-users in response to national measures implemented to achieve the RED obligations. As these national measures may differ per Member State, they may not result in a coherent EU-wide demand for vehicles able to run on specific biofuels or e-fuels.

Adapting the HDV CO_2 regulation such that the use of biofuels / e-fuels is rewarded under that legislation, does not appear easily feasible, due to the fact that OEMs do not have control over a) whether the fuel used in a diesel engine is bio-diesel / e-diesel or conventional diesel, and b) whether alternative fuels used, e.g. in dedicated engines, are produced from renewable or fossil energy sources. If these fuels, other than blended into regular diesel meeting the EN590 standard, are to play a significant role in the timely decarbonization of the HD road transport sector, specific measures at the EU-level may be required to provide a more direct incentive to OEMs to develop and market vehicles that can use these fuels and to consolidate the demand for a limited number of alternative fuel variants. Assessing or proposing options for additional policies or amendments to existing regulations to promote the development of vehicles running on e-fuels, however, is beyond the scope of this project.

9.9 Low- and Zero-Emission Zones

9.9.1 Description

An increasing number of European cities have or plan to set entry regulations defining Low- (LE) and Zero-Emission (ZE) Zones. The regulations include areas with restricted access depending on vehicle class, fuel type, vocation, etc., but differ between cities. In the Netherlands, the cities of Amsterdam, Den Haag, Rotterdam, and Utrecht are among the municipalities which have introduced low emission zones for trucks (Urban Access Regulations in Europe, 2022). As part of the Dutch Climate Agreement it has been agreed that 30 to 40 of the larger municipalities in the Netherlands will introduce zero emission zones for city logistics as of 2025. In other European Member States and cities comparable plans are being developed.

9.9.2 Implications on different energy carriers

Zero-emission zones are currently defined as zones in which only vans and lorries will be allowed to drive that do not emit any tailpipe emissions within the designated zone. In this definition combustion engines will not be allowed within these areas, regardless of the fuel used. This would also be the case for H_2-ICE as combustion of hydrogen results in nitrogen oxide emissions. Based on currently available technologies only hydrogen fuel cell and battery electric vans and lorries would be allowed. The situation for hybrid-electric vehicles, which combine an ICE with battery-electric propulsion and the possibility of a ZE-mode, is more complex and a general statement is not possible. Under the current Dutch ZE policy, plug-in hybrids in ZE mode will be allowed in ZE zones until 2030 only, provided that the use of the ZE-mode can be monitored and accounted.

9.10 Possible new policies in the near future

As part of the Fit for 55 Package, the European Commission is considering the introduction of a separate CO_2 emission trading system for buildings and road transport (ETS-BRT)[52]. The CO_2 allowance price under this "cap & trade" system will be different from the allowance price under the existing EU ETS, applicable to stationary installations (e.g., large industries and power plants) and aviation. A merger of the two systems in the further future is considered possible.

Applying a carbon price to fossil fuels will shorten the pay-back time for energy saving investments in buildings and road transport, and will improve the competitiveness of renewable energy carriers such as the e-fuels studied in this report, as it increased the price of fossil fuels relative to renewable alternatives[53].

At the COP 26 in Glasgow fifteen countries and several transport sector companies spread across four continents signed an agreement that aims for all new heavy goods vehicles and buses in their countries to be zero emission from 2040[54]. If this would at some point translate into EU legislation that effectively bans the use of internal combustion engines in trucks, biofuels and e-fuels would cease to be a viable option for decarbonizing heavy duty road transport. The part of the market that battery-electric propulsion (possibly in combination with "electric road systems", such as overhead wires in combination with catenary systems) cannot cater for, would then need to be powered by hydrogen fuel cells. Despite the promising development of the performance and costs of battery-electric trucks, the results of this study do not support a decision to narrow down the options to BEVs and FCEVs. Uncertainties with respect to further development of the performance and costs of both technologies, combined with significant challenges associated with implementing charging infrastructure and the distribution of hydrogen, motivate to "keep more horses in the race".

9.11 Summary and conclusions

An overview of which energy carriers are affected by certain legislative acts and standards is given in Table 35. The impact is scored as + / o / -, depending on whether the policy instrument provides a direct positive or negative incentive for the application of different options or does not have a direct impact.

52 COM(2021) 551 final, see e.g. https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf

53 As an example: A carbon price of 100 €/tonne leads to a price increase for fossil diesel of 0.26 €/litre.

54 See https://globaldrivetozero.org/MOU/

Table 35: Effects of different types of legislation / standards on vehicles with different energy carriers

Legislation / Effect on	BEV electricity	FCEV H_2	ICEV fossil	ICEV e-fuel	ICEV H_2
Regulations 49 and 85**	o	o	o	o/-**	-**
RED	+	+	-	+	+
FQD	o	o	-	+	+
EN / ISO fuel standards	o	o	o	o/-***	o/-****
AFID/AFIR	+	+	o	o	+
CO_2 Regulation for HDVs	+	+	o*	o*	+
ZE zones*****	+	+	-	-	-

*) The HDV CO_2 regulation does promote efficiency improvements in ICEVs.

**) Currently H_2-ICE and engines running on e-methanol and e-DME cannot be approved or certified under these regulations.

***) EN / ISO fuel standards are not available for all considered e-fuels.

****) Fuel cell grade H_2 can be used in hydrogen combustion engines. If the tolerance of H_2-ICE for lower fuel quality is to be utilized an alternative fuel standard may need to be developed.

*****) Whether ICEVs / electric hybrids will be allowed depends on country specific regulations. In The Netherlands, such vehicles will be allowed only until 2030, provided that the use of the ZE-mode can be monitored and accounted.

All of the regulations, directives and other types of policies and standards discussed in this chapter have their own objectives. They have been set up in such a way that the various objectives are met effectively. As a result, different drivetrains and energy carriers are affected by these policies in different ways. In general a combination of several policy instruments is needed to enable and promote the uptake of new fuels / energy carriers or new vehicle technologies, providing incentives to stakeholders in different parts of the value chain (fuel / energy producers and distributors, vehicle manufacturers, end users). As such different policy measures may contribute to the same GHG emission reduction (e.g. the HDV CO_2 regulation, incentivizing the marketing of electric vehicles and the AFIR promoting the deployment of charging infrastructure) or may produce complementary GHG emission reductions (such as the HDV CO_2 regulation, incentivizing the efficiency improvement in ICEVs and the RED, promoting the reduction in well-to-wheel emissions of the fuels used in ICEVs). European policies are generally complemented by Member State policies such as fiscal incentives or subsidies. Together the policies contribute to reducing the overall CO_2 emissions of road transport in Europe.

However, in some cases certain drivetrain technologies or energy carriers were not available at the time that a certain policy was developed or amended. Even though the uptake of such technologies may contribute to meeting the policy's objective efficiently, they may not be included in a way that they are incentivized or not be included at all. In such cases amendments of the existing policy instruments may be necessary enable and/or promote the uptake of new technologies or energy carriers. In this chapter such policy gaps are identified. Developing or proposing solutions, however, is beyond the scope of this project. It is, however, noted that due to the mentioned interaction of different policy measures in many cases amendments to more than one policy instrument may be needed and that these amendments must maintain the coherent interaction between the policy instruments.

Currently, combustion engine vehicles running on fuels other than petrol, diesel, LPG or CNG/LNG cannot be type approved because they are not included in regulation 85. Examples of such other fuels are hydrogen, (e-)methanol, (e-)DME. Moreover, under the current policy design, they cannot be Euro VI certified because they are not catered for in regulation 49. This is all due to the fact that these drivetrains and energy carriers were not available in sufficient amounts to include them in these regulations and directives. As these technologies are progressing, there comes a point at which it has to be decided whether to adjust existing regulations in such a way that they also cater for these technologies. This is especially relevant for technologies that could play a role in achieving the ambitions of the European Commission. This is the case for all the technologies considered in this report because of their potential contribution to decarbonization of heavy-duty road transport. Since these regulations do not interact directly with other policies, these regulations could be adjusted to cater for these technologies.

The legislation related to the CO_2 emissions of heavy-duty vehicles is primarily focused on improving the efficiency of vehicles powered by internal combustion engines fueled with diesel from fossil sources. Besides that, its focus on tailpipe emissions also provides strong incentives for OEMs to develop and market BEVs and FCEVs. H_2-ICEVs in principle also count as zero-emission option under this regulation, but as discussed above amendments to the type approval regulation 85 are necessary to enable the marketing of these vehicles.

As tailpipe CO_2 emissions are the regulated parameter of the HDV CO_2 regulation, the use of renewable equivalents of fossil fuels (biofuels or synthetic) is not incentivized under this directive. Standardized fuel compositions for diesel, petrol, LPG and CNG/LNG are used in vehicle engines during type approval testing. Even if renewable equivalents for the standardized test fuel compositions for diesel, petrol, LPG and CNG/LNG were allowed during testing, the tailpipe CO_2 emissions would be very similar, as the amount of carbon per unit of energy in the alternative fuels is very similar to that in the conventional test fuel.

The Renewable Energy Directive (REDII) strives to increase the share of renewable sources for energy in all sectors, including the transport sector. It sets minimum targets for the share of renewables in energy use. These renewable sources include renewable electricity and hydrogen as well as biomass derived fuels, e-fuels and recycled carbon-based fuels as long as they meet the criteria set in the directive. Therefore, in contrast to the CO_2 regulation for HDVs, the REDII does incentivize the use of renewable equivalents of fossil fuels as well as alternative renewable fuels. The proposal for the REDIII includes a new sub-target for e-fuels, i.e., that 2.6% of the energy supplied to the transport sector should be met by e-fuels by 2030. Whether or not the incentives in the REDII and in the proposal for the REDIII are strong enough to achieve EU decarbonization goals requires an elaborate study and is therefore outside the scope of this project.

Under the current Fuel Quality Directive the focus is on fuels for internal combustion engines (petrol, diesel, gas-oil). BEVs and FCEVs are not affected. The FQD currently includes a GHG-emission reduction target of 6%. Similar to the REDII this can be achieved with multiple renewable fuel types, such as fuels derived from biomass or e-fuels.

If the use of e-fuels in trucks is to play a role in meeting medium and longer term climate goals, adaptations to the current legislative framework are necessary.
The HDV CO_2 regulation and the RED thus interact to promote the application of energy efficient vehicles running on renewable energy carriers, including e-fuels. However, neither the HDV CO_2 regulation nor the RED provide direct incentives to OEMs for developing vehicles running on e-fuels. At the same time it is recognised that HDV OEMs need to make efforts, in terms of investments in R&D, product development, production capacity and marketing, to enable the application of e-fuels other than e-diesel and e-LNG. The development of demand from end users depends on varying Member State implementations of the RED and on other national policies, which increases the risk associated with such investments by OEMs and may lead to higher technology costs, if scattered demand for different alternative fuels hinders economies-of-scale in the production of dedicated engines. If e-fuels, other than e-diesel and e-LNG, are to play a significant role in the timely decarbonization of the HD road transport sector, specific measures at the EU-level are required to accelerate the development and marketing of dedicated vehicles.

Important to note, in this context, is that crediting of e-fuels and biofuels, in the way it is currently done by the RED, is only valuable from the perspective of new vehicles[55] as long as future HDV CO_2 emission targets are not completely prohibiting tailpipe CO_2 emissions. With the current design of the regulation, demanding that from some point onwards all new HDVs should be zero emission would completely rule out the production and sales of combustion engine vehicles running on carbon-based fuels. Based on the results of this study, which do indicate that there will likely be a long term need for combustion engines in at least some parts of the HDV fleet, a ZE target by e.g. 2035 or 2040 for HDVs based on tailpipe emissions[56] seems neither feasible nor sensible. It is therefore recommended that options are explored at the EU level, e.g. for adaptations to existing legislation, that stimulate OEMs to develop and market clean and efficient combustion engines that are able to run on sustainable carbon-based fuels.

The distribution of alternative energy carriers / fuels still poses a challenge. Whilst infrastructure for supply of petrol, diesel and – to a lesser extent – CNG and LNG is readily available and can to a large extent also be used for alternative fuels like synthetic fuels, there is still room for improvement with respect to charging infrastructure and hydrogen supply points. Based on the proposal for a revision of the AFID, it can be expected that also for electricity and hydrogen a minimum infrastructure network will be built up throughout the EU in the coming decades. As e-fuels and biofuels can to a large extent make use of the existing infrastructure for liquid and gaseous fossil fuels, this regulation will not directly support the availability of biofuels or e-fuels.

Zero-emission zones are established by municipalities. Although there are similarities between the individual measures of different cities, they do not follow a common framework. That makes an assessment of which energy carriers are affected in which way rather difficult. However, the goal of reducing emissions in city centers generally means restricted or no access for ICEVs. The situation for hybrid-electric vehicles is more complex and a general statement is not possible. Under the current Dutch ZE policy, plug-in hybrids in ZE mode will be allowed in ZE zones until 2030 only, provided that the use of the ZE-mode can be monitored and accounted. BEVs and FCEVs face no limitations of that kind, and thus are the primary alternatives promoted by this instrument.

55 Using renewable fuels in the existing fleet, provided these fuels are compatible with existing engines, obviously remains a useful means for contributing to CO_2 emission reduction in the road freight sector.

56 Such as e.g. proposed by fifteen countries and several transport sector companies, which, at the climate summit in Glasgow in 2021, signed an agreement that aims for all new heavy goods vehicles and buses in their countries to be zero emission from 2040.

-10-
Conclusions and discussion

In this chapter the results of assessments with respect to different criteria from the previous chapters are summarized and related to each other to determine the relevance and potential of e-fuels for decarbonizing heavy duty road transport. Furthermore, the effect on the results of important uncertainties in the assumptions used or in external developments are discussed.

It should be emphasized that all conclusions drawn in this chapter relate to the application of different energy carriers in long haul trucks. In other applications a similar comparative assessment may lead to different conclusions.

10.1 Value-case analysis results

10.1.1 Energy efficiency

All the alternative energy carrier solutions considered in this study rely on green electricity. As long as renewable energy is a scarce resource, the efficiency with which it is used remains an important criterion for assessing decarbonisation options. The energy chain efficiency also affects costs and land-use impacts of decarbonisation options.

It is expected that the electricity demand will significantly increase in the coming decades. Other modalities than long haul road transport as well as other sectors than mobility (such as industry or built environment) are expected to also have an increased demand for green electricity in the coming decades. Therefore, (green) electricity is expected to remain scarce, especially so long as we rely on renewable energy production in the Netherlands or the EU, and energy efficiency will remain an important assessment parameter from a societal perspective for the decades to come. As soon as imported H_2 or e-fuels from other regions become affordable and abundantly available, then the energy efficiency criterion would become less critical. Future reliance on imported renewable energy or fuels, however, may not reduce the dependency on other (politically instable) regions that we also try to avoid by moving away from fossil fuels.

Regarding overall energy chain efficiency (from renewable energy generation to the wheel), battery electric drivetrain solutions perform roughly a factor four to five better than the other energy carriers assessed.

For hydrogen distribution by means of tube trailers is found to be a very energy-inefficient process, contributing significant to the WTW energy consumption per kilometre drive. The chain energy efficiency is expected to improve significantly if pipelines were (partly) to be used in the future for the distribution of hydrogen of if hydrogen could be produced at the filling station. These options, however, have, not been assessed in this study.

10.1.2 Emissions

Only battery electric and fuel cell electric drivetrains produce truly zero tailpipe emissions (except for water). Even though e-fuels in combination with an internal combustion engine do emit CO_2 emissions from the tailpipe, these emissions can be considered 'carbon-neutral' if the carbon was obtained by direct air capture (extracted from the atmosphere).

The combustion of e-fuels or hydrogen in ICEs also results in pollutant emissions such as PM and NO_x. Increased stringency of EU policy has resulted in a significant reduction of such emissions over the last decades, and further improvements are expected from the Euro VII limits which are under development. No significant differences in pollutant emission performance are expected for ICEVs running on the e-fuels studied here as these fuels are very similar to fossil equivalents and aftertreatment systems will respond similarly.

10.1.3 Cost

For a commercial application such as long-haul freight transport by tractor-trailer the total cost of ownership of a new technology is one of the more important drivers for its uptake.

In this study projections for battery electric vehicles indicate that this is going to be the most cost-effective solution in the longer term. The energy cost of battery electric vehicles is expected to be lower per km than that of other alternative energy carriers assessed. This is due to lower production costs (resulting from high energy chain efficiencies) and distribution costs. The vehicle costs are higher than for alternative fuels, but are expected to come down significantly mainly due to the expected reduction of battery prices, which does not only rely on the demand from the heavy duty road sector. The cost of fuel cell vehicles is also expected to reduce, but compared to batteries, the demand for fuel cells in other sectors is expected to be more limited. This may hinder cost reductions for fuel cell trucks. The TCO of ICEVs running on e-fuels is expected to be close to that of hydrogen fuel cell vehicles. Therefore, apart from electric trucks, the expected future TCO of all technologies assessed is found to be so close that cost is not a strong distinguishing criterion.

10.1.4 Commercial readiness

Of the net zero CO_2 energy carriers assessed, production of renewable electricity is most mature. Technologies such as PV and wind turbines are already extensively deployed globally. The production of green hydrogen is currently still limited. The CRL of e-fuel production is currently even lower, reflected by the fact that no e-fuels are currently produced on a large scale. Certain elements of the production chain are already more mature, however, such as Fischer-Tropsch synthesis which is also used for producing GTL diesel.

On the other hand, vehicles in which e-diesel and to a lower extent e-LNG can be used have the highest CRL of the drivetrains assessed. Heavy duty road vehicles with fuel cells or with battery electric drivetrains are already being produced but are currently at a lower commercial readiness level. The CRL of battery electric trucks is expected to increase significantly in the next decade, partly driven by advancements made in the light duty sector.

The scale of public hydrogen and recharging infrastructure is currently too low for a large scale roll out of heavy duty vehicles depending on these energy carriers. A significant increase of availability may be expected partly due to European regulation (AFIR). The main challenges for upscaling charging infrastructure for electric trucks relate to the integration of charging locations with high power demand into the electricity supply network and the integration of charging into the logistic planning. Technology for fast charging of trucks is still in a development and demonstration phase. Upscaling will require significant reinforcement of the electricity grid. Where projections with respect to vehicle performance and TCO indicate that battery-electric propulsion will be suitable for a very large share of all truck applications, the speed with which appropriate charging infrastructure can be implemented and integrated in the energy supply system is a major uncertainty for realising that share. This aspect was not part of the scope of this study.

Upscaling of hydrogen tank infrastructure requires locations to which hydrogen can be distributed at limited cost (connected to hydrogen pipeline) or that allow for local production. Moreover, standardisation of pressure is important. Infrastructure for e-fuels is not arranged in the proposed AFIR and therefore a minimum amount is not guaranteed. On the other hand, if demand for carbon-based fuels (with e-fuels or biofuels gradually replacing fossil fuels) would remain substantial, part of the current infrastructure for conventional fuels can be maintained.

10.1.5 Safety

Of the energy carriers assessed, diesel and therefore also e-diesel is the fuel with the lowest safety risk. It is flammable but has a low explosion risk. Gaseous energy carriers (LNG and hydrogen) have significantly higher explosion risks and are therefore more hazardous. The low temperature (LNG) or high pressure (H_2) require more sophisticated storage and handling. Overall, this results in higher risks compared to conventional fuels. When looking at the possible consequences of fuel catching fire or exploding after loss of containment due a traffic incident, it was found that the so-called effect distance is roughly the same for diesel, methanol, and pressurized hydrogen. For LNG, however, it is more than twice as large as that of diesel.

Finally, for battery electric vehicles most factors result in low risk and low effort for safe usage. The two main concerns are the run-away reaction that is possible in some batteries and the risks related to the presence of a voltage difference and possibly toxic fumes (in case of fire) in case of salvage and rescue.

In general, the use of alternative fuels poses higher risks than the use of diesel. To ensure sufficient safety, proper containment and handling needs to be ensured and mitigating measures will be required to reduce the risk of dangerous failure. These measures can be aimed at either reducing the possible consequences of (a single) failure or reducing the likelihood of failure. Examples of measures that can be taken are introducing monitoring systems, system design following a safe life design approach, or a damage tolerant system.

10.2 Policy and legislation

In order for alternative drivetrain types and energy carriers to be developed and taken up by end users, in general policies and legislation are required that promote their development and deployment. As a minimum requirement policies and standards need to be in place that allow these technologies and products to find their way to the market without unnecessary or impassable hurdles. Moreover, policies should be designed in such a way that the alternative technologies, that are favorable from a societal perspective (based on their contribution to various societal objectives such as low cost, improved health or increased sustainability), are also attractive for end users.

Different policy instruments have different objectives, such as:

- Incentivizing / enforcing the deployment of energy carriers that are favorable from a societal perspective: REDII and FQD;
- Incentivizing / enforcing improvement of certain vehicle characteristics: CO_2 standards (aimed at improving energy efficiency to reduce CO_2 emissions) and the weight and dimensions directive;
- Assuring that certain boundary conditions are met with respect to facilitating the uptake of new technologies by end users: the AFID aims at realizing a minimum required level of charging and refueling infrastructure.

Policies and legislation tend to run behind technological developments. Only when technologies reach a certain state of maturity, it is identified whether existing policies cater well enough for these new developments and changes are potentially made. Policies and legislation are therefore ever evolving.

Current policies and legislation do not allow combustion engine vehicles running on hydrogen, (e-) methanol or (e-)DME to be type approved or Euro VI certified, This blocks their uptake and therefore limits further technological development. However, the process of catering for these relatively new technologies has already started and it is expected that in the near future this will no longer be a problem.

The Renewable Energy Directive (REDII) promotes the marketing of renewable fuels for transport, with a focus on sustainable biofuels. The proposed update of the directive (REDIII) also contains specific targets for hydrogen and e-fuels.

The European HDV CO_2 regulation is primarily designed to promote efficiency improvement and CO_2 reduction in conventional trucks. As the regulation targets tailpipe CO_2 emissions, it also strongly promotes the introduction of electric vehicles and vehicles running on hydrogen. The HDV CO_2 regulation and the RED thus interact to promote the application of energy efficient vehicles running on renewable energy carriers, including e-fuels.

However, neither the HDV CO_2 regulation nor the RED provide direct incentives to OEMs for developing vehicles running on e-fuels. The development of demand for such vehicles from end users is uncertain as it depends on varying Member State implementations of the RED and on other national policies. If e-fuels, other than e-diesel and e-LNG, are to play a significant role in the timely decarbonization of the HD road transport sector, specific measures at the EU-level are required to accelerate the development and marketing of dedicated vehicles. It is recommended that options are explored at the EU level, e.g. for adaptations to existing legislation, that stimulate OEMs to develop and market clean and efficient combustion engines that are able to run on sustainable carbon-based fuels.

Important to note is that, from the perspective of new vehicle sales, this crediting of e-fuels and biofuels is only valuable as long as the future CO_2 emission targets are not completely prohibiting tailpipe CO_2 emissions. Based on the results of this study, which do indicate that there will likely be a long term need for combustion engines in at least some parts of the HDV fleet, and on the uncertainties associated with the timely realization of sufficient high-power charging infrastructure, a ZE target by e.g. 2035 or 2040 for HDVs based on tailpipe emissions seems neither feasible nor sensible. As there will likely be a long term need for combustion engines in at least some parts of the HDV fleet, it is recommended that options are explored at the EU level, e.g. for adaptations to existing legislation, that stimulate OEMs to develop and market clean and efficient combustion engines that are able to run on sustainable carbon-based fuels, such as e-fuels.

An evaluation of whether current policies and legislation are sufficient to achieve an uptake of the various drivetrain types and energy carriers that corresponds to what would be most desirable from a societal perspective is beyond the scope of this project.

10.3 Uncertainties & external influences

For zero-emission trucks (BEVs and FCEVs), besides technological and economic feasibility, a number of external influences play a role in the eventual uptake of these vehicles.

Cost developments are inherently uncertain. In Chapter 5 the cost projections based on several literature sources are provided. Should battery prices or fuel cell prices decrease slower than expected, for example due to material shortages because of a high demand or global supply chain problems, a slower uptake of these vehicles can be expected. If on the other hand affordable e-fuels become readily available (from regions with relatively low levelized cost of green electricity), e.g., due to demand for other modalities such as maritime and aviation, e-fuels can become more interesting for road transport also (for vehicles that do not enter zero-emission zones). In this case synergy with developments in other sectors and the rest of the world influence the uptake of e-fuels in heavy road transport in the Netherlands.

Also, the range improvements of electric and to a lesser extent hydrogen trucks are uncertain. In case these do not increase as much as expected (e.g., due to less energy density improvement), the flexibility of trucks will be lower making them less suitable for certain types of deployment, i.e. high mileages and / or high variation in daily mileage.

Revolutionizing technologies such as solid-state batteries (increasing the range of battery electric vehicles), or cheap hydrogen from excess electricity or imported from other regions, work in favour of the uptake of these technologies

The extent to which BEVs and FCEVs and possibly H_2-ICEVs are able to meet the needs of trucks will determine the size of the remaining niche for e-fuels. If that niche becomes too small, it may not be worthwhile to build new distribution infrastructure and only e-diesel remains as an option.

As mentioned above the speed with which energy distribution infrastructure can be realized is also an important uncertainty, specifically for electric trucks and hydrogen.

The availability of e-fuels for road transport will depend heavily on the supply for and demand from aviation and shipping.

10.4 Overall conclusions

In the table below a summary of the scores on the assessed criteria is presented for all options assessed in this study. The upper part reflects the situation in the near future, while the bottom part reflects the further future (2040 – 2050).

Table 36: Summary in terms of scores on the considered criteria relative to fossil diesel for the periods 2020-2030 and 2040-2050. Improvements over time are shown as green cells.

			Emissions					CRL level		
		Energy chain efficiency (WTW)	CO_2 emissions (WTW)	Pollutants (TTW)	TCO	Applicability / flexibility	Safety	CRL vehicle	CRL infra-structure	CRL fuel production
2020	**ICEV** (fossil diesel)	o	o	o	o	o	o	o	o	o
	ICEV (e-diesel)	---	+++	o	--	o	o	o	o	---
	ICEV (e-methanol)	--	+++	o	--	-	-	-	---	---
	ICEV (e-DME)	--	+++	o	--	-	--	-	---	---
	ICEV (e-LNG)	--	+++	o	----	-	--	o	-	---
	ICEV (green H_2)	--	+++	o	---	---	--	-	--	--
	FCEV (green H_2)	-	+++	+	---	---	--	---	--	--
	BEV (green electricity)	+	+++	+	--	----	-	--	---	-
2030	**ICEV** (fossil diesel)	o	o	o	o	o	o	o	o	o
	ICEV (e-diesel)	---	+++	o	--	o	o	o	o	-
	ICEV (e-methanol)	--	+++	o	--	-	-	?	?	-
	ICEV (e-DME)	--	+++	o	--	-	--	?	?	-
	ICEV (e-LNG)	--	+++	o	---	-	--	o	-	-
	ICEV (green H_2)	--	+++	o	--	--	--	-	-	+
	FCEV (green H_2)	-	+++	+	--	--	--	--	-	+
	BEV (green electricity)	+	+++	+	-	---	-	-	-	++
2040*	**ICEV** (fossil diesel)	o	o	o	o	o	o	o	o	o
	ICEV (e-methanol)	--	+++	o	-	-	-	?	?	+
	BEV (green electricity)	+	+++	+	o	--	-	?	?	++

*) For 2040 assessments were only done for a limited number of energy carriers due to lack of available data

As shown in Table 36, each energy carrier has specific strengths and weaknesses and there is not one energy carrier that performs best on all criteria on which they are assessed in this study. In other words, there is no 'silver bullet'. However, especially in the short term, e-diesel and battery electric trucks perform well for many of the indicators assessed. On the other hand, both also have significant drawbacks. In the short term, e-diesel will not be commercially ready and even in the far future its energy chain will remain inefficient. Also, air polluting tailpipe emissions will remain, albeit at very lower levels once Euro VII standards are in place. At this moment, electric trucks are hardly available, recharging infrastructure is insufficiently available for a fast uptake and their range / flexibility is lower compared to other options. The position of battery electric trucks is likely to improve over time compared to the other energy carriers and drivetrain types assessed. The TCO is expected to improve significantly, and more infrastructure will very likely be developed, partly driven by European regulation. The range / flexibility of electric trucks is likely to improve as well but will remain lower than that of other energy carriers / drivetrain types assessed. Nevertheless, the expected range increase to 450 – 550 km on a single battery charge should be sufficient for deployment in a large share of Dutch trucks as 92% drive less than 500 km/day on average.

Thus, if e-diesel would be considered at this point in time, it would rank very high especially when deployed in locations where air pollution is less of an issue i.e., outside of urban areas with stringent policy objectives for air quality[57]. These arguments also hold for certain sustainable biofuels that require CRL improvements and that are only limitedly available, e.g., FT-diesel from biomass or lignocellulosic ethanol. In time however, due to expected battery improvements (price and energy density), battery electric trucks will likely become a viable option, especially for applications that do not require very high flexibility. Thus, a ramp-up of e-fuels for road transport may come too late for a large share of heavy-duty road transport.

However, for certain types of deployment (i.e., high flexibility) other solutions than battery-electric may be required. There are three options to make a shift to zero GHG emission transport in these cases:

- Electric tractor swapping: allowing one tractor to recharge while another drives on will require more trucks and therefore lead to higher cost but does not require an additional infrastructure network. However, such a solution requires significant coordination from the logistics companies to limit the risk of time loss, especially relevant for refrigerated trailers.
- E-fuels or hydrogen: The TCO of e-diesel and fuel cell trucks are expected to be close in the future. Hydrogen fuel cell vehicles have the advantage of being completely zero-emission but require the build-up of a complete infrastructure network, including pipelines for (part of) the distribution, that may only be used by a selective group of vehicles. Contrarily, e-diesel has the advantage of an existing infrastructure and better safety but will never be completely without pollutant emissions.
- In motion charging of electric trucks (also known as electric road system): The issue of limited range is mainly with very long-distance trucks. Most of these drive significant distances over stretches of highways. Overhead wires and catenary systems may power electric trucks, limiting the required battery capacity and recharging times. Less recharging time would allow for longer distances in the same driving period. Lower battery costs are compensated by higher infrastructure costs.
- Modal shift to inland shipping or trains: Especially the latter is in most cases already a zero-emission transport mode that can cover long distances. The capacity of this option, however, is limited and it is not suitable for all types of goods currently transported by long haul trucks.
- The latter three options would also become relevant in case of insufficient availability or recharging infrastructure or slower battery cost reduction than expected.

In conclusion, battery-electric tractors are expected to have several advantages over the other energy carriers and propulsion technologies evaluated. In the decades to come, the technological development of batteries and charging infrastructure will allow battery-electric freight vehicles to be used for increasingly demanding trips, making this technology suitable for an increasing share of freight vehicles.

However, it is likely that even in the longer term not all journeys can be driven by battery-electric freight vehicles. In case of high required flexibility and/or insufficient charging points (e.g., due to insufficient grid capacity) and/or high battery prices (e.g., due to lack of critical materials) other solutions may be necessary. Several solutions are possible, such as the use of other energy carriers (hydrogen, e-fuels, or

57 As mentioned above, the impact of the pollution still remaining with the upcoming Euro-VII emission legislation is extremely low.

biofuels), logistic changes (modal shift or switching electric tractors) or charging while driving ('in motion charging'). How many of these solutions will be applied depends, among other things, on the development of battery technology and the possibility of (rapid) charging, as well as on as yet undetermined preferences of the energy supply sector and the end-users for one or more specific fuels.

The smaller the share of the fleet that cannot drive electrically, the less market share remains for other solutions. This means that the risk will be greater for solutions that require substantial investments that must be earned back solely or largely through this uncertain market share. This applies for example to hydrogen (investments required in the supply of hydrogen to refuelling stations) and in-motion charging (investments required in overhead power lines). For the other solutions, the risks are lower because they are likely to be used in other applications (e-fuels for shipping and aviation or as platform molecule in the chemical industry) or because no additional investment is needed (some biofuels and e-fuels can use existing infrastructure).

Especially in the short term, (blended) biofuels as transition fuels can play an important role in the decarbonisation of heavy long-distance transport for which battery-electricity is not a suitable alternative. If this role can be taken over or supplemented in the longer term by using e-fuels, use can be made of the existing fuel infrastructure to a large extent. However, e-fuels are expected to compete with other solutions for a limited part of heavy goods transport, so the extent to which they will be used is still very uncertain.

-11- References

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-A-

Energy carriers WTT routes

Table 37: WTT Expended energy – electricity (JRC, 2020).

		Electricity EU 2030	Electricity from wind energy
		EMEL1b	**EMEL1/ CH2b**
Production & conditioning at source			
Transformation at source			
Transportation to market			
Transformation near market	Wind turbine		0
	Power plant	1.1	
Conditioning & distribution	Distribution HV	0.03	0.03
	Distribution MV		0.01
	Distribution LV		0.03
Total WTT efficiency [%]		**45%**	**93%**

Table 38: WTT Expended energy – hydrogen (JRC, 2020).

		Grey hydrogen compressed	Green hydrogen compressed	Green hydrogen liquified
		EMEL1/CH2b	**WDEL1/CH2**	**WDEL1/LH1**
Production & conditioning at source	*NA*			
Transformation at source	*NA*			
Transportation to market	*NA*			
Transformation near market	Wind turbine	0	0	
	Distribution HV	0.04	0.04	0.04
	Power plant	1.90		
	Electrolysis	0.55	0.55	0.55
	H_2 liquefaction			0.31
Conditioning & distribution	H_2 pipeline	0.00		
	H_2 compression and dispensing at retail site	0.22	0.28	
	L-H_2 road transport			0.04
	L-H_2 dispensing at retail site (cryo-compression)			0.03
Total [$MJ/MJ_{hydrogen}$]		**2.7**	**0.9**	**1.0**
Total WTT efficiency [%]		**27%**	**54%**	**51%**

Table 39: WTT Expended energy – e-fuels (JRC, 2020)

		e-Diesel	e-Methanol	e-DME
		RESD2c	REME1a	REDE1a
Production & conditioning at source	Wind power plant	0	0	0
Transformation at source	NA			
Transportation to market	Electricity transport	0.05	0.07	0.07
Transformation near market	Hydrogen via electrolysis		0.66	0.68
	Methanol synthesis		0.53	0.54
	DME synthesis			0.07
	HT electrolysis, RWGS, FT synthesis, upgrading	1.76		
Conditioning & distribution	Distribution	0.01	0.02	0.02
	Dispensing at retail site	0.01	0.01	0.01
Total [MJ/MJ]		**1.8**	**1.3**	**1.4**
Total WTT efficiency [%]		**35%**	**44%**	**42%**

Table 40: CO_{2eq} emissions WTT – electricity (JRC, 2020)

		Electricity EU 2030	**Electricity from wind energy**
		EMEL1b	**EMEL1/ CH2b**
Production & conditioning at source			
Transformation at source			
Transportation to market			
Transformation near market	Wind turbine		
	Power plant	71	
Conditioning & distribution	Distribution HV		
	Distribution MV		
	Distribution LV		
Total [gCO2eq/MJ]		**71**	**0**

Table 41: CO_{2eq} emissions WTT – hydrogen (JRC, 2020)

		Grey hydrogen compressed	Green hydrogen compressed	Green hydrogen liquified
		EMEL1/CH2b	**WDEL1/CH2**	**WDEL1/LH1**
Production & conditioning at source	*NA*			
Transformation at source	*NA*			
Transportation to market	*NA*			
Transformation near market	Wind turbine			
	Power plant	112		
	Electrolysis			
	Distribution HV			
	H_2 liquefaction			
Conditioning & distribution	H_2 pipeline			
	H_2 compression and dispensing at retail site	6.4	9.5	
	L-H_2 road transport			2.5
	L-H_2 dispensing at retail site (cryo-compres-sion)			1.1
Total [gCO2eq/MJ]		**118**	**0.9**	**1.0**

Table 42: CO_{2eq} emissions WTT – e-fuels (JRC, 2020)

		e-Diesel	e-Methanol	e-DME
		RESD2c	**REME1a**	**REDE1a**
Production & conditioning at source	Wind power plant	0	0	0
Transformation at source	NA			
Transportation to market	Electricity transport	0	0	0
Transformation near market	Hydrogen via electrolysis		0	0
	Methanol synthesis		0	0
	DME synthesis			0
	HT electrolysis, RWGS, FT synthesis, upgrading	0.08		
Conditioning & distribution	distribution	0.47	1.4	1.3
	Dispensing at retail site	0.25	0.4	0.4
Total [gCO2eq/MJ]		**0.8**	**1.8**	**1.7**

-B-

Vehicle dimensioning and cost assumptions

Table 43: Summary of powertrain dimensions for the bottom-up cost analysis.

	Diesel ICE	H_2-ICE	BEV	FCEV
Fuel tank capacity	600 L	80 kg	-	45 kg
Battery size	-	-	400/750 kWh[58]	70 kWh
Engine/Fuel Cell Power	330 kW	330 kW	-	300 kW
Electric Motor Power	-	-	330 kW	330 kW

Table 44: Component costs based on literature

Component	Units	Source	2020	2030	2040
Glider	€/vehicle	TNO, 2021	60,000	60,000	60,000
Diesel/e-Diesel ICE					
Diesel ICE	€/kW	Oostdam, 2019	65	65	65
Emission Control Systems (Euro VI SCR)	€/Unit	Fries et al., 2017	6,300	8,190	10,650
Diesel Fuel Tank	€/L	Extrapolated from original spare part price	1.45	1.45	1.45
e-LNG					
Additional cost per vehicle	€/vehicle	TNO, 2020	30,000	30,000	30,000
e-Methanol/e-DME ICE					
Additional cost per vehicle	€/vehicle	TNO, 2020	7,500	7,500	7,500
BEV/FCEV					
Electric Motor	€/kW	ICCT, 2017	18	14	12
Inverter	€/vehicle		600	500	450
Control Units and BMU	€/vehicle		300	270	243
Wiring Harness	€/vehicle	Leoni, 2019	900	670	603

58 80% Depth-of-Discharge assumed here

Table 45: Component costs for sensitivity analysis

Sensitivities	Units	Scenario	Source	2020	2030	2040
Electric Batteries (Pack-level cost)	€/kWh	High	European Commission, 2019; Hsieh et al., 2019	400	200	147
		Mid	Mauler et al., 2021	234	132	92
		Low	Schmidt et al., 2017; Nykvist et al., 2019; Schmidt et al., 2019	124	43	33[59]
Fuel Cell Stack (System-level cost)	€/kW	High	Ricardo E&E, 2017	430	280	253
		Mid	Topsector Logistiek, 2019; FCH-Roland Berger, 2020	210	155	90
		Low	FCH-Roland Berger Optimistic, 2020	80	55	50
H_2-Tank	€/kg	High	Oostdam, 2019	1000	640	400
		Mid	Ricardo et al., 2016; CE Delft-TNO, 2012	630	400	300
		Low	FCH-Roland Berger, 2020	500	350	250

Table 46: Projected CAPEX values (in thousand Euros) for trucks with various drivetrains. For the years between 2020-2030 and 2030-2040, linear interpolation is used.

		2020	2030	2040
ICE-diesel	-	89	91	91
ICE e-LNG	-	119	121	121
ICE (DME/E-Methanol)	-	96	98	98
ICE-H_2	High	168	141	123
	Mid	138	122	114
	Low	128	118	110
BEV – large battery	High	372	245	216
	Mid	342	189	161
	Low	218	108	102
BEV – small battery	High	232	164	148
	Mid	219	132	119
	Low	153	90	87
FCEV	High	370	191	176
	Mid	254	152	123
	Low	175	114	105

59 Interpolated from values for 2030 and 2050.

-C-

Methodology for analysing logistics truck deployment data

The data used in the analysis shown in section 2.4:

- is based on data that is provided by Overbeek from 1 Jan. 2018 until 31 May 2018;
- has been retrieved via an API with the (Transics) FMS system;
- includes vehicle information with a five minute interval including vehicle ID, company ID, time, location (longitude and latitude at a certain timestamp) and velocity (in km/h at a certain timestamp).

In order to determine the travelled distances, trip durations and waiting times the data is processed and enriched via an extensive data processing pipeline. This includes a route and trip recognition algorithm and a map matching stage as can be seen in Figure 40.

Route and trip recognition. The timeseries from the FMS platform of the trucks includes all points in which the ignition of the vehicle was turned on. This ensures that no points are missed, but not all those timeseries are relevant for this analysis. To select the subset of points where the vehicle is on the road with finite speed between an origin and destination, routes are identified. A route is then the set of timeseries between origin and destination where the vehicle's speed is higher than zero. The origin and the destination are determined as the places where the vehicle spent more than 15 minutes without moving. Note that the origins and destinations are not necessarily contiguous in the original dataset. Given a perfect dataset one would expect that previous destination can be considered as the origin for the next route. However in practice it can happen that, due to GPS inaccuracies (parts of) a route are not registered. Vehicles can also temporarily remain stationary for periods shorter than the threshold defined to be considered a final destination (e.g. when refuelling). These segments of time series define what we call a stop. Several stops can take place within the same trip. The different timeseries that constitute a route are referred as trips. Every route consists of trips with the number of stops in the trip. The definition of routes and trips is illustrated in figure

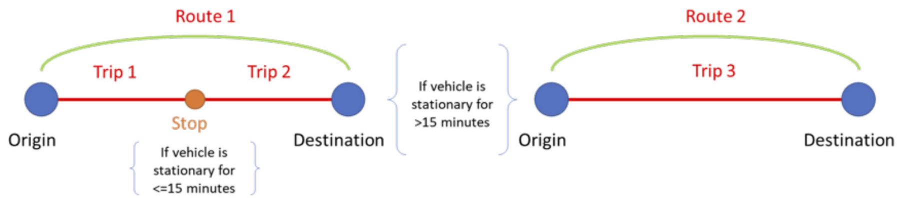

Figure 39: Representation of routes and trips

Map Matching. The dataset records the position of the vehicle based on Global Navigation Satellite System (GNSS), meaning that the timeseries are in latitude and longitude to a reference world shape model. Given that datapoints from vehicles are collected every five minutes the straight lines between the points not necessarily depict the trajectory that the vehicle drove in reality. By Map Matching the serial GPS positions are related to the edges in a predefined network graph. In order to do so, the

Open-Source Routing Machine (OSRM) (Luxen & Vetter, 2011) has been used. OSRM is a system that, given a sequence of points and times, determines what is the most likely route in the real network that was taken. From the OSRM we obtain the specific links from the network that correspond to each of the points.

When processing the dataset it was considered that trips might be interrelated. e.g. when a vehicle drives from Rotterdam to Antwerp and back. Moreover given that a driver might overnight in the vehicle it is likely that vehicles visit a sequence of (consecutive) destinations. As part of the data analysis it became apparent that the vehicle activity on Sundays decreased considerably. Based on this observation the, the data was analysed in continuous pieces each containing an entire week from Monday morning to Sunday night.

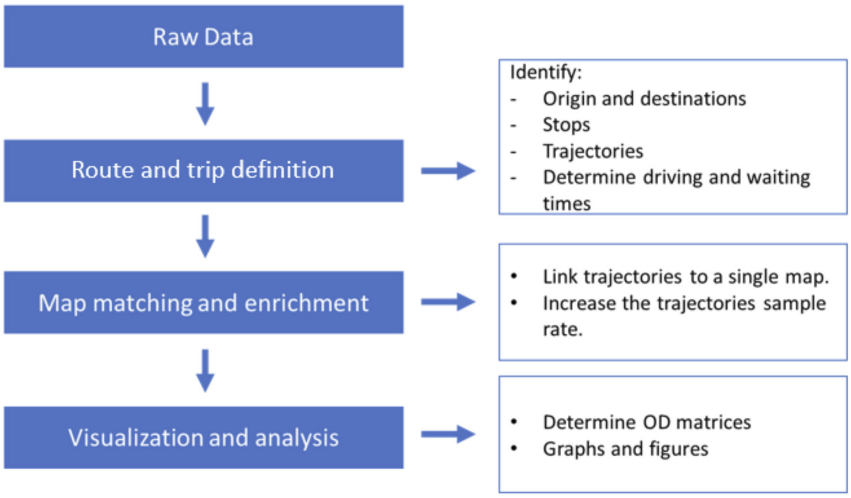

Figure 40: Pre-processing of the data breakdown

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