GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

STUDY OF ALTERNATIVES FOR THE TRANSITION TOWARDS ZERO-EMISSION FREIGHT TRANSPORT IN SPAIN

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Study of alternatives for the transition towards zero-emission freight transport in Spain

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ESTUDIO DE ALTERNATIVAS PARA LA TRANSICIÓN HACIA EL TRANSPORTE DE MERCANCÍAS DE CERO EMISIONES EN ESPAÑA

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RESUMEN

1. *INTRODUCCIÓN*

El transporte de mercancías por carretera desempeña un papel clave en el crecimiento económico, así como en el cambio climático y en la salud pública. De hecho, este tipo de transporte es el responsable de producir aproximadamente el 6 % de las emisiones totales de gases de efecto invernadero (GEIs) de la Unión Europea. Además, el transporte de mercancías por carretera no sólo produce GEIs, sino también $PM_{2,5}$ y NO_x, lo que desencadena la formación de O_3 y $PM_{2,5}$ adicionales. Todos estos son contaminantes del aire que causan graves problemas de salud que pueden provocar muertes prematuras. [1], [2], [3]

Este trabajo de fin de grado se centra en estudiar alternativas encaminadas hacia el transporte de mercancías por carretera cero emisiones en España. Para ello, se estudiarán las diferentes tecnologías disponibles para la transición hacia medios de transporte de cero emisiones, centrándose especialmente en los vehículos pesados.

Para ello se caracterizarán los camiones eléctricos de batería (BETs), de pila de combustible (FCETs), de Gas Natural Comprimido (GNC), e-diésel, diésel y de Aceite Vegetal Hidro-tratado (HVO). Para estas tecnologías, el CAPEX, OPEX y TCO para 2023, 2030 y 2040 se calcularán considerando una tasa de descuento del 9,5 % y una vida útil de 5 años, que es, en promedio, el primer período de tenencia del usuario.

Además, se establecerá el vector energético de cada una de las tecnologías estudiadas en base a escenarios previstos para el periodo 2023-2040 para analizar el nivel de dependencia de España de terceros países en función de las diferentes fuentes energéticas. Además, para los mismos escenarios se cuantificará la demanda para estimar de forma orientativa la infraestructura requerida.

2. METODOLOGÍA

En primer lugar, se requiere describir la flota estudiada, la cual está compuesta por camiones pertenecientes a la categoría 5-LH VECTO que se refiere a semirremolques de largo recorrido con un peso superior a 16 toneladas, una potencia nominal de 350 kW, un eje 4x2 y un chasis tractor. Además, para lograr una mayor profundidad en el desarrollo del proyecto, el grupo 5-LH se ha subdividido en tres subcategorías en función del rango diario de distancia recorrida por el camión: 500 km, 800 km y 1.000 km. [4], [5]

En segundo lugar, se proporciona una visión de las diferentes tecnologías para comprender los principios básicos de funcionamiento de cada una de ellas, así como sus principales componentes clave, que son relevantes más adelante para calcular el CAPEX.

Para este proyecto se ha diseñado un *Caso Base* para cada tecnología para calcular su CAPEX, OPEX y TCO. Para el *Caso Base*, el coste de los diferentes componentes del camión para el CAPEX, como por ejemplo el tren motriz o el sistema de almacenamiento de energía; los peajes, los costes y consumos de combustible o los costes de operación y mantenimiento para el OPEX y otros parámetros como el salario del conductor o el valor residual necesarios para calcular el TCO se han obtenido calculando medias ponderadas a partir de valores proporcionados por una amplia variedad de fuentes fiables. Todo esto se explica en profundidad en el *Capítulo 3. Cálculo del TCO*.

Las fórmulas utilizadas para el cálculo del CAPEX, OPEX y TCO para el *Caso Base* así como los demás escenarios establecidos son las siguientes [6]:

$$CAPEX = Tren\ motriz + almacenamiento\ de\ energía + resto\ del\ camión$$

$$OPEX = Peajes + Coste\ del\ combustible\ (incluida\ la\ infraestructura\ de\ recarga) + Salario\ del\ conductor + Seguro + O\&M$$

$$TCO = \frac{\left(CAPEX - SUB - \frac{SV}{(1+i)^N}\right) \cdot CRF + \frac{1}{N} \cdot \sum_{n=1}^{N} \frac{OPEX}{(1+i)^n}}{AKT}$$

$$CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1}$$

Siendo “i” el valor de la tasa de descuento (9,5 %), “N” la vida útil del camión (5 años), “AKT” los kilómetros anuales recorridos, “SUB” los subsidios otorgados por el gobierno y “SV” el valor residual o de achatarramiento.

3. Resultados

Para el *Caso Base* los resultados obtenidos son los siguientes dependiendo de si se consideran las tarifas de CO_2 en carretera (OPEX_1 y TCO_1) o no (OPEX_2 y TCO_2). Estas tasas se propusieron en la Directiva Euroviñeta para considerar el coste externo de las emisiones de CO_2 de los camiones que no son cero emisiones y supuestamente deben aplicarse desde el 2023 en adelante en la UE. Sin embargo, algunos estados miembros están retrasando su entrada en vigor.

TCO para cada tecnología (500 km de recorrido diario)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	454.920	190.601	190.601	2,03	2,03
BET	358.453	119.993	119.993	1,41	1,41
CNG	149.611	183.988	174.447	1,40	1,34
HVO	137.243	151.560	142.019	1,22	1,16
e-diesel	137.243	193.664	184.123	1,49	1,43
Diesel	137.243	146.434	136.893	1,18	1,12

Tabla 1: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 500 km en 2023.

TCO para cada tecnología (500 km de recorrido diario)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	222.114	139.307	139.307	1,25	1,25	219.922	127.404	127.404	1,18	1,18
BET	182.176	110.551	110.551	0,99	0,99	189.700	114.964	114.964	1,05	1,05
CNG	165.736	169.445	159.904	1,35	1,28	202.401	174.095	164.554	1,46	1,39
HVO	157.479	142.616	133.075	1,20	1,14	193.184	147.279	137.738	1,31	1,25
e-diesel	157.479	166.411	156.870	1,36	1,29	193.184	171.350	161.809	1,47	1,40
Diesel	157.479	138.742	129.202	1,18	1,12	193.184	143.405	133.864	1,29	1,22

Tabla 2: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 500 km en 2030 y 2040.

TCO para cada tecnología (800 km de recorrido diario)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	502.802	245.473	245.473	1,85	1,85
BET	486.920	145.667	145.667	1,40	1,40
CNG	154.184	231.399	218.731	1,29	1,22
HVO	138.288	187.810	175.142	1,09	1,03
e-diesel	138.288	243.715	231.047	1,36	1,30
Diesel	138.288	181.004	168.336	1,06	0,99

Tabla 3: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 800 km en 2023.

TCO para cada tecnología (800 km de recorrido diario)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	242.927	170.063	170.063	1,11	1,11	235.878	152.449	152.449	1,02	1,02
BET	229.862	130.196	130.196	0,90	0,90	228.574	134.430	134.430	0,93	0,93
CNG	172.882	211.599	198.931	1,22	1,16	210.740	216.239	203.572	1,30	1,24
HVO	158.720	175.051	162.383	1,06	1,00	194.772	179.713	167.045	1,14	1,08
e-diesel	158.720	206.645	193.977	1,21	1,15	194.772	211.675	199.007	1,30	1,23
Diesel	158.720	169.908	157.240	1,03	0,97	194.772	174.570	161.902	1,12	1,05

Tabla 4: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 800 km en 2030 y 2040.

TCO para cada tecnología (1000 km de recorrido diario)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	525.033	290.922	290.922	1,68	1,68
BET	561.503	225.571	225.571	1,51	1,51
CNG	154.184	282.906	266.790	1,21	1,15
HVO	138.984	225.040	208.924	1,00	0,94
e-diesel	138.984	296.160	280.044	1,27	1,21
Diesel	138.984	213.290	197.174	0,95	0,89

Tabla 5: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 1.000 km en 2023.

TCO para cada tecnología (1000 km de recorrido diario)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	258.933	196.707	196.707	0,99	0,99	246.516	173.726	173.726	0,89	0,89
BET	263.694	193.908	193.908	0,99	0,99	256.154	198.120	198.120	1,00	1,00
CNG	173.541	256.034	239.918	1,13	1,07	211.510	260.653	244.538	1,20	1,13
HVO	159.547	207.885	191.770	0,96	0,90	195.832	212.548	196.432	1,02	0,96
e-diesel	159.547	248.077	231.962	1,11	1,05	195.832	253.207	237.092	1,18	1,12
Diesel	159.547	199.006	182.890	0,92	0,86	195.832	203.668	187.553	0,99	0,93

Tabla 6: CAPEX (€), OPEX (€) y TCO (€/km) para camiones con un recorrido diario de 1.000 km en 2030 y 2040.

Después de estos resultados iniciales del *Caso Base*, se realizó un análisis de sensibilidad. En el *Caso 1*, para 2030 y 2040 se consideraron las estimaciones más bajas realizadas por fuentes cercanas al mercado para los precios de las baterías, mientras que los parámetros seleccionados para 2023 se corresponden con los del *Caso Base*, ya que no hay cambios significativos en los datos recogidos por las diversas fuentes para este año. La *Tabla 7* muestra los resultados obtenidos para el CAPEX y el TCO 1 & 2 de los BETs, que están exentos de los cargos por CO_2 en carretera, ya que estos resultados son los únicos que cambian en comparación con los del *Caso Base*. [7], [8]

Resultados del Caso 1						
	500 km recorrido diario		800 km recorrido diario		1000 km recorrido diario	
	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2
	2023					
BET	358.453	1,41	486.920	1,40	561.503	1,51
	2030					
BET	177.448	0,98	222.243	0,89	254.025	0,98
	2040					
BET	180.510	1,03	213.766	0,90	237.360	0,97

Tabla 7: CAPEX (€) y TCO (€/km) para el Caso 1de los BETs en función del recorrido diario para 2023, 2030 y 2040.

Por el contrario, para el *Caso 2* el parámetro que cambia con respecto al *Caso Base* es el coste de la pila de combustible, para el cual se han seleccionado los precios propuestos por en fuentes cercanas al mercado, que son las más optimistas, para los años 2023, 2030 y 2040. La *Tabla 8* muestra los resultados obtenidos para el CAPEX y el TCO 1 & 2 de los FCETs, que están exentos de las tasas de CO_2 en carretera, ya que son los únicos que cambian en comparación con los resultados del *Caso Base*. [7], [9]

Resultados del Caso 2						
	500 km recorrido diario		800 km recorrido diario		1000 km recorrido diario	
	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2
	2023					
FCET	348.572	1,80	396.454	1,68	418.685	1,54
	2030					
FCET	206.153	1,22	226.967	1,09	238.860	0,97
	2040					
FCET	198.578	1,13	214.534	0,99	225.171	0,87

Tabla 8: CAPEX (€) y TCO (€/km) para el Caso 2 de los FCETs en función del recorrido diario para 2023, 2030 y 2040.

En cuanto al *Caso 3*, se ha considerado un escenario pesimista en lo que respecta a los precios del diésel, suponiendo un precio medio de venta al público de 1,75 €/l sin IVA para 2023, 2030 y 2040. La *Tabla 9* muestra los valores obtenidos para el OPEX_1, OPEX_2, TCO_1 y TCO_2 de los camiones diésel. El CAPEX de los camiones diésel y los resultados obtenidos para el resto las de tecnologías son los del *Caso Base*. [9]

Resultados del Caso 3												
	500 km recorrido diario				800km recorrido diario				1000 km recorrido diario			
	OPEX 1	OPEX 2	TCO 1	TCO 2	OPEX 1	OPEX 2	TCO 1	TCO 2	OPEX 1	OPEX 2	TCO 1	TCO 2
	2023											
Diésel	165.839	156.298	1,31	1,25	206.769	194.101	1,18	1,12	249.159	233.043	1,09	1,03
	2030											
Diésel	153.407	143.866	1,27	1,21	189.378	176.710	1,13	1,07	226.112	209.996	1,03	0,97
	2040											
Diésel	158.069	148.528	1,38	1,32	194.041	181.373	1,21	1,15	230.775	214.659	1,09	1,03

Tabla 9: OPEX_1, OPEX_2 (€) y TCO_1, TCO_2 (€/km) para el Caso 3 de los camiones diésel dependiendo de su recorrido diario para 2023, 2030 y 2040.

En cuanto al *Caso 4*, se ha considerado que el precio de la electricidad sin IVA disminuirá para 2030 y 2040 un 25 % y un 50 % respectivamente en comparación con 2023, año para el cual se han mantenido los precios del *Caso Base* para las diferentes autonomías diarias. En la *Tabla 10* se pueden observar el OPEX 1 & 2, así como el TCO 1 & 2 para los BETs. Estos valores para los BETs son los únicos que cambian, ya que el CAPEX y los resultados para el resto de tecnologías estudiadas son los del *Caso Base*. [10]

Resultados del Caso 4						
	500 km recorrido diario		800 km recorrido diario		1000 km recorrido diario	
	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2
	2023					
BET	119.993	1,41	145.667	1,40	225.571	1,51
	2030					
BET	103.338	0,95	120.980	0,86	171.259	0,90
	2040					
BET	100.538	0,95	115.998	0,84	152.822	0,83

Tabla 10: OPEX 1 & 2 (€) y TCO 1 & 2 (€/km) para el Caso 4 de los BETs en función de su recorrido diario para 2023, 2030 y 2040.

Finalmente, para el *Caso 5*, se ha considerado una disminución del 20 % en el precio sin IVA del hidrógeno en el surtidor en comparación con el *Caso Base* para 2030 y 2040. La *Tabla 11* muestra el OPEX 1 & 2, así como el TCO 1 & 2. para los FCETs ya que estos valores son los únicos que cambian, mientras que el CAPEX los resultados obtenidos para las otras tecnologías son los del *Caso Base*. [9]

Resultados del Caso 5						
	500 km recorrido diario		800 km recorrido diario		1000 km recorrido diario	
	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2
	2023					
FCET	190.601	2,03	245.473	1,85	290.922	1,68
	2030					
FCET	127.947	1,18	154.905	1,04	178.232	0,92
	2040					
FCET	119.311	1,12	141.647	0,97	160.673	0,84

Table 11: OPEX 1 & 2 (€) y TCO 1 & 2 (€/km) para el Caso 5 de los FCETs en función de su recorrido diario para 2023, 2030 y 2040.

Además, en el *Capítulo 5. Discusión* se han dado posibles escenarios para la composición de la flota de camiones española en función de la cantidad de camiones matriculados para 2022 y de los resultados del TCO obtenidos en el *Capítulo 4. Resultados* para el *Caso Base*. A partir de estos escenarios se ha pronosticado la demanda de 2023, 2030 y 2040 y se ha evaluado la dependencia energética española de terceros países.[4], [11], [12], [13], [14], [15], [16], [17], [18], [19]

Para 2023, se considera que el 99 % de la flota de camiones 5-LH funciona con diésel, mientras que el 0,22 % funciona exclusivamente con biometano (bio-GNC) -datos del parque de camiones para 2022- (*Figura 1*). Esto implica que para 2023 se requieren alrededor de 123 millones de kg de biometano (1.591 GWh) y 65,45 mil millones de litros de diésel, de los cuales el 8,5 % son biodiesel. [11], [12], [20], [21], [22]

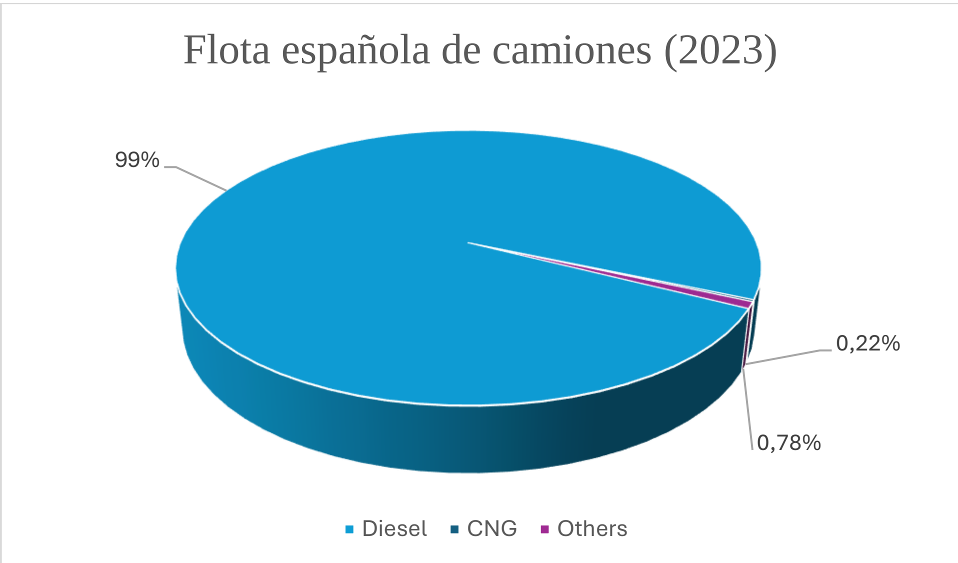

Figura 1: Flota española de camiones 5-LH para 2023.

Para 2030, se estima que la flota española de camiones se distribuye de la siguiente manera para camiones 5-LH con recorridos diarios de 500 km y 800 km: 75 % camiones diésel, 15 % BETs, 8 % camiones HVO y 2 % camiones GNC, mientras que para los camiones 5-LH con 1.000 km de recorrido diario la flota estaría compuesta por un 85 % de camiones diésel, un 8 % de camiones HVO, un 5 % de BETs y un 2 % de camiones de GNC (*Figuras 2 y 3*).

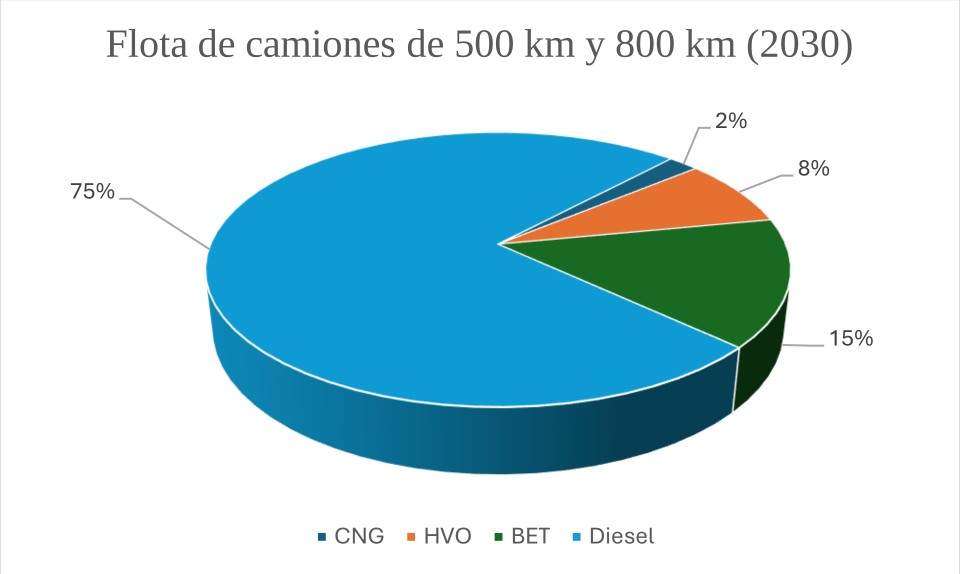

Figura 2: Flota española de camiones 5-LH con recorridos diarios de 500 km y 800 km para 2030.

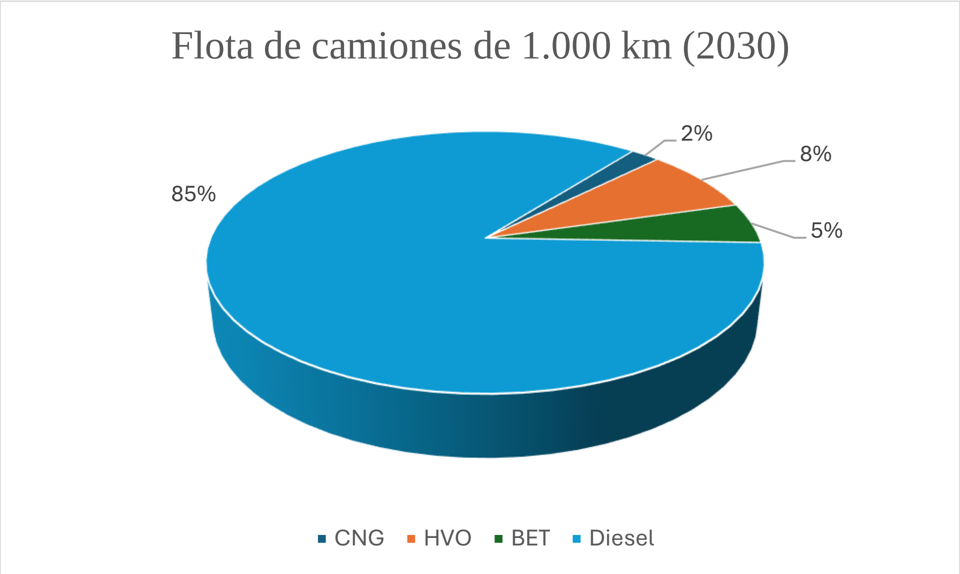

Figura 3: Flota española de camiones 5-LH con recorrido diario de 1.000 km para 2030.

Por lo tanto, las cantidades totales de combustible necesarias para 2030 para los camiones 5-LH según el escenario hipotético propuesto son: 880 millones de kg de biometano (11.382 GWh), 4 mil millones de litros de HVO, 22.582 GWh para los BETs y 39,57 mil millones de litros de diésel, de los cuales el 10 % son biodiesel. [8], [12], [13], [15], [16] Para 2040, se estima que la flota de camiones estará compuesta por un 50 % de camiones diésel, un 30 % de BETs, un 14,7 % de FCET, un 5 % de camiones HVO y un 0,3 % de camiones de GNC en el caso de camiones con recorridos diarios de 500 km y 800 km, mientras que para los camiones con recorrido diario de 1.000 km se estima la flota se distribuye así: 77 % camiones diésel, 10 % camiones HVO, 3 % BETs, 0,3 % camiones GNC y 9,7 % FCETs (*Figuras 4 y 5*).

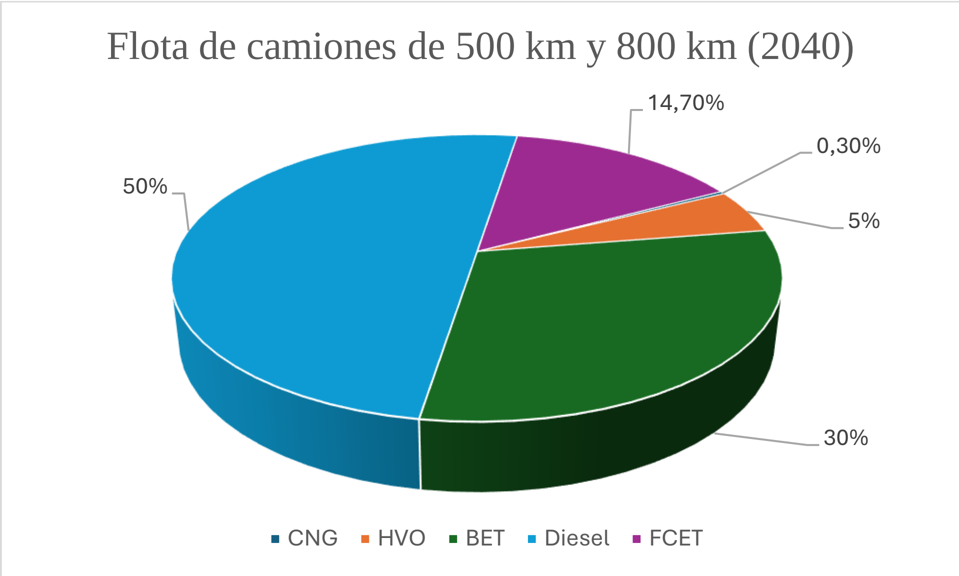

Figura 4: Flota española de camiones 5-LH con recorridos diarios de 500 km y 800 km para 2040.

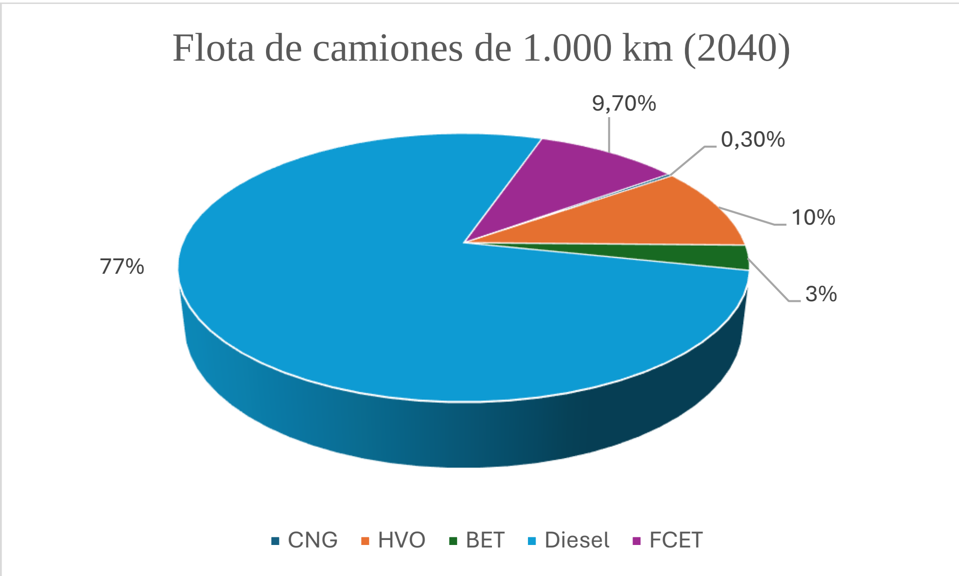

Figura 5: Flota española de camiones 5-LH con recorrido diario de 1.000 km para 2040.

Como resultado, las cantidades totales de combustible necesarias para 2040 según el escenario anterior se estiman en 132 millones de kg de biometano (1.708 GWh), 3,55 mil millones de litros de HVO, 38.857 GWh para BET, 1,59 mil millones de kg de hidrógeno y 30,65 mil millones de litros de diésel de los cuales el 10 % son biodiesel. [8], [17]

En cuanto a las infraestructuras de repostaje, se ha revisado la red española actual para las diferentes tecnologías, así como las distintas normativas europeas para ver si España ya las cumple actualmente o, en caso contrario, si es probable que España las cumpla en un futuro próximo. [11], [18], [19], [23], [24], [25]

4. CONCLUSIONES

En este proyecto se ha calculado y analizado el CAPEX, OPEX y TCO para camiones diésel, e-diésel, HVO, bio-GNC, de batería y de pila de combustible así como el nivel de dependencia de España de terceros países para suministrar la demanda de combustible de la flota de camiones 5-LH española y las infraestructuras de repostaje disponibles y previstas para determinar la viabilidad de las diferentes tecnologías. Las principales conclusiones extraídas son las siguientes:

<u>En cuanto al CAPEX</u>

- En 2023 los FCETs y BETs tienen los mayores CAPEX, y existe una gran brecha entre ellos y el precio de venta al público del resto de tecnologías. Sin embargo, se espera que sean las tecnologías con mayor reducción de CAPEX a lo largo del periodo 2023-2040 (en torno al 50%).
- Las importantes reducciones estimadas en el precio de la batería -para los BETs- y del sistema de pila de combustible -para los FCETs- durante el período 2023-2040 es en gran medida lo que hace que estas tecnologías sean más competitivas y estén considerablemente menos afectadas por la inflación para 2030 y 2040.
- Pese a ello, en 2040 los camiones diésel, HVO y e-diésel seguirán teniendo el CAPEX más bajo para aquellos con un recorrido diario de 800 km y 1.000 km debido a la gran batería y pila de combustible que requieren los FCTEs y BETs para ser viables. Por el contrario, los BETs tienen el CAPEX más bajo para 2040 para camiones con una autonomía de conducción diaria de 500 km.
- Se espera que los CAPEX de los camiones GNC, diésel, e-diésel y HVO aumenten de 2023 a 2040 debido principalmente a la inflación, ya que se consideran tecnologías maduras y, por tanto, totalmente desarrolladas.

<u>En términos de OPEX y TCO</u>

- Para recorridos diarios de 500 km y 800 km los BETs tienen el OPEX más competitivo durante el periodo estudiado principalmente por su eficiencia y bajos costes de recarga al recargar el 80 % de las veces en sus depósitos.
- Sin embargo, para recorridos diarios de 1.000 km los BETs no son tan competitivos porque se asume que cargan principalmente en estaciones públicas,

lo que encarece considerablemente el precio por recarga ya que la infraestructura es de mayor potencia.

- En términos de OPEX y TCO, la mejor opción a largo plazo para sustituir a los camiones diésel de 1.000 km de recorrido diario es la de los FCET.
- Los camiones a bio-GNC y e-diésel son competitivos en términos de TCO para 2023 debido a sus bajos CAPEX. Sin embargo, a partir de 2030 dejan de ser competitivos porque sus OPEX siguen siendo elevados comparado con los del resto de tecnologías. Otra razón es que sus CAPEX aumentan al igual que los de otras tecnologías maduras, mientras que los FCETs y BETs experimentan importantes reducciones de CAPEX.
- Es probable que para 2030 la mayoría de los camiones 5-LH sean diésel, eléctricos de batería o HVO, mientras que para 2040 lo más probable es que el peso de los BETs y los FCETs aumente notablemente, dependiendo de la distancia diaria recorrida.
- Para recorridos diarios de 500 km y 800 km, en 2030 hay TCOs más competitivos que los del diésel, independientemente de la aplicación de las tasas de CO_2, mientras que para recorridos diarios de 1,000 km el diésel tiene los TCOs más baratos hasta 2040.

<u>En relación con los análisis de sensibilidad</u>

- La selección de los valores más optimistas para las baterías de los BETs hace que sean aún más competitivos para 2030 y 2040 para recorridos diarios de 500 km y 800 km a pesar de tener ya el TCO más bajo en el *Caso Base*. Sin embargo, para los camiones de 1.000 km, esta predicción optimista solo reduce el TCO de los BETs lo suficiente como para que se conviertan en la segunda tecnología más competitiva en 2040 si se aplican las tarifas de CO_2, por detrás de los FCETs.
- El optimismo en la reducción del precio de venta al público de los sistemas de pila de combustible no es suficiente para que los FCETs se posicionen mejor en los rankings de TCO salvo para los FCET de 1.000 km, que se convierten en la tercera tecnología más competitiva para 2030.
- Para 2040, un precio de venta al público del diésel de 1,75 €/l sin IVA implica que BETs, FCETs y HVO se convierten en las tecnologías más competitivas.
- Considerando una disminución del 25 % y del 50 % en el precio de la electricidad para 2030 y 2040 respecto al de 2023, los BETs se convierten en la tecnología más competitiva en términos de TCO para todos los recorridos diarios en 2040.
- Una disminución del 20 % en el precio sin IVA del hidrógeno en el surtidor no implica ningún cambio en las clasificaciones de TCO en 2040 para los FCETs.

<u>Dependencia de terceros países para cubrir la demanda de combustible española en 2023</u>

- Para 2023, España depende en gran medida de terceros países no pertenecientes a la UE para importar petróleo crudo, mientras que depende parcialmente de los países de la UE para cubrir la demanda esperada de biodiesel y biometano.

Dependencia de terceros y demanda de combustible española en 2030

- La demanda de combustible esperada para 2030 es de alrededor de 11,4 mil GWh de biometano, alrededor de 4 mil millones de litros de HVO, 22,6 mil GWh de electricidad y 39,57 mil millones de litros de diésel, de los cuales 3,96 mil millones de litros son biodiesel (10%).
- Para 2030 se espera que España cubra alrededor de una cuarta parte de la demanda de biometano y al menos el 24,1 % y el 26,4 % de la demanda de HVO y biodiesel respectivamente, dependiendo probablemente sólo de otros países de la UE para cubrir la parte restante. Además, se espera que el 51,6 % de la demanda total de electricidad se produzca con fuentes de energía renovables, por lo que España sólo dependería de países de la UE y de fuera de la UE para el 48,4 % de la electricidad necesaria. Además, el petróleo crudo se importa en su totalidad desde terceros estados no miembros de la UE.

Dependencia de terceros y demanda de combustible española en 2040

- La demanda de combustible prevista para 2040 es de alrededor de 1,71 mil GWh de biometano, 3,55 mil millones de litros de HVO, 38,86 mil GWh de electricidad, 1,6 mil millones de kg de hidrógeno y 30,65 mil millones de litros de diésel, de los cuales 3,07 litros son biodiesel (10%).
- Para 2040 se espera que España sea capaz de cubrir cerca de la mitad de la demanda de biometano y al menos el 27,2 %, el 20,4 % y el 37,8 % de la demanda de HVO, biodiesel e hidrógeno respectivamente, siendo la demanda restante abastecida por países de la UE o países como Brasil o Egipto en el caso del hidrógeno verde. Además, se espera que para 2040 alrededor del 80 % de la electricidad necesaria se produzca a partir de fuentes de energía renovables, así que España sólo dependería de países de la UE y de fuera de la UE para el 20 % de la electricidad necesaria. Por último, es necesario importar petróleo crudo de terceros países no miembros de la UE.

Infraestructura de recarga española

- La red española de gasineras cumple con la normativa AFIR, por lo que la infraestructura de repostaje no debería limitar la adopción de esta tecnología.
- España está actualmente lejos de cumplir la regulación AFIR en materia de hidrogeneras y es probable que tampoco la cumpla en 2030, lo que hace poco probable que los FCETs aumenten su cuota de mercado antes del 2040 por la falta de infraestructuras de repostaje.
- A pesar del aumento de cargadores de una potencia mínima disponible de 350 kW, la mayor parte de la red TEN-T española no cubre actualmente la regulación AFIR. Sin embargo, de cara a 2030 España podría conseguir cumplir con dicha regulación.

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STUDY OF ALTERNATIVES FOR THE TRANSITION TOWARDS ZERO-EMISSION FREIGHT TRANSPORT IN SPAIN

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ABSTRACT

1. INTRODUCTION

Road freight transport plays a key role in economic growth as well as in climate change and public health. Indeed, road freight transport in the European Union is responsible for producing around 6 % of its total Green House Gases (GHGs) emissions. Moreover, road freight transport not only produces GHGs but also $PM_{2.5}$ and NO_x, which triggers the formation of O_3 and additional $PM_{2.5}$. All of these are air pollutants which cause serious health conditions that can lead to premature deaths. [1], [2], [3]

This final degree project focuses on studying alternatives towards zero-emission freight transport by road in Spain. In order to do so, the different technologies available for transitioning to zero-emission means of transport will be studied, particularly focusing on heavy-duty vehicles.

For doing so, battery electric, fuel cell, Compressed Natural Gas (CNG), e-diesel, diesel and Hydrotreated Vegetable Oil (HVO) trucks will be characterised. For these technologies the CAPEX, OPEX and TCO for 2023, 2030 and 2040 will be computed considering a 9.5 % discount rate and a lifetime of 5 years, which is the first user holding period on average.

Additionally, the energy vector for each of the studied technologies based on predicted scenarios will be established for the 2023-2040 period for analysing Spain's level of dependency on third countries based on the different energy sources. Furthermore, for the same scenarios the demand will be quantified for estimating the required infrastructure as a guideline.

2. METHODOLOGY

Firstly, it is required to describe the studied fleet which is composed of trucks belonging to the 5-LH VECTO category which refers to long-haul tractor trailers weighting more than 16 tones with a 350 kW power unit rating, a 4x2 axis and a tractor chassis. Moreover, for achieving greater depth in the development of the project the 5-LH group has been subdivided into three subcategories based on the truck's daily driving range: 500 km, 800 km and 1,000 km. [4], [5]

Secondly, an insight on the different technologies is provided for understanding the functioning basic principles of each of them as well as their main key components, which are relevant later for computing the CAPEX.

For this project, a *Base Case* has been designed for each technology for computing their CAPEX, OPEX and TCO. For the *Base Case,* the cost of the different trucks' components for the CAPEX such as the powertrain or the energy storage system; the road tolls, fuel costs and consumption or the operations and maintenance costs for the OPEX and other parameters such as the driver wage or the scrappage value needed for computing the TCO have been obtained by calculating weighted averages from values provided by a wide variety of reliable sources. All of this is explained in depth in *Chapter 3. TCO calculation*.

The formulas used for computing the CAPEX, OPEX and TCO for the Base Case as well as the other established scenarios are the following [6]:

$$CAPEX = Powertrain + energy\ storage + rest\ of\ the\ truck$$

$$OPEX = Tolls + Fuel\ costs\ (including\ charging\ infrastructure) + Driver\ wages + Insurance + O\&M$$

$$TCO = \frac{\left(CAPEX - SUB - \frac{SV}{(1+i)^N}\right) \cdot CRF + \frac{1}{N} \cdot \sum_{n=1}^{N} \frac{OPEX}{(1+i)^n}}{AKT}$$

$$CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1}$$

Being "i" the discount rate value (9.5 %), "N" the lifetime of the truck (5 years), "AKT" the annual kilometres travelled, "SUB" the subsidies provided by the government and "SV" the scrappage value.

3. RESULTS

For the *Base Case* the obtained results are the following depending on if CO_2 road fees considered (OPEX_1 and TCO_1) or not (OPEX_2 and TCO_2). These fees were proposed in the Eurovignette Directive for considering the external cost of CO_2 emissions of non-zero-emission trucks and are supposed to be applied in the different European member states from 2023 onwards, yet some EU countries are delaying it.

TCO for each technology (500 km driving range)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	454.920	190.601	190.601	2,03	2,03
BET	358.453	119.993	119.993	1,41	1,41
CNG	149.611	183.988	174.447	1,40	1,34
HVO	137.243	151.560	142.019	1,22	1,16
e-diesel	137.243	193.664	184.123	1,49	1,43
Diesel	137.243	146.434	136.893	1,18	1,12

Table 1: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with a 500 km daily driving range for 2023.

TCO for each technology (500 km driving range)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	222.114	139.307	139.307	1,25	1,25	219.922	127.404	127.404	1,18	1,18
BET	182.176	110.551	110.551	0,99	0,99	189.700	114.964	114.964	1,05	1,05
CNG	165.736	169.445	159.904	1,35	1,28	202.401	174.095	164.554	1,46	1,39
HVO	157.479	142.616	133.075	1,20	1,14	193.184	147.279	137.738	1,31	1,25
e-diesel	157.479	166.411	156.870	1,36	1,29	193.184	171.350	161.809	1,47	1,40
Diesel	157.479	138.742	129.202	1,18	1,12	193.184	143.405	133.864	1,29	1,22

Table 2: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with a 500 km daily driving range for 2030 and 2040.

TCO for each technology (800 km driving range) (€)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	502.802	245.473	245.473	1,85	1,85
BET	486.920	145.667	145.667	1,40	1,40
CNG	154.184	231.399	218.731	1,29	1,22
HVO	138.288	187.810	175.142	1,09	1,03
e-diesel	138.288	243.715	231.047	1,36	1,30
Diesel	138.288	181.004	168.336	1,06	0,99

Table 3: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with an 800 km daily driving range for 2023.

TCO for each technology (800 km driving range) (€)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	242.927	170.063	170.063	1,11	1,11	235.878	152.449	152.449	1,02	1,02
BET	229.862	130.196	130.196	0,90	0,90	228.574	134.430	134.430	0,93	0,93
CNG	172.882	211.599	198.931	1,22	1,16	210.740	216.239	203.572	1,30	1,24
HVO	158.720	175.051	162.383	1,06	1,00	194.772	179.713	167.045	1,14	1,08
e-diesel	158.720	206.645	193.977	1,21	1,15	194.772	211.675	199.007	1,30	1,23
Diesel	158.720	169.908	157.240	1,03	0,97	194.772	174.570	161.902	1,12	1,05

Table 4: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with an 800 km daily driving range for 2030 and 2040.

TCO for each technology (1000 km driving range) (€)					
	2023				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	525.033	290.922	290.922	1,68	1,68
BET	561.503	225.571	225.571	1,51	1,51
CNG	154.184	282.906	266.790	1,21	1,15
HVO	138.984	225.040	208.924	1,00	0,94
e-diesel	138.984	296.160	280.044	1,27	1,21
Diesel	138.984	213.290	197.174	0,95	0,89

Table 5: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with a 1,000 km daily driving range for 2023.

TCO for each technology (1000 km driving range) (€)										
	2030					2040				
	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2	CAPEX	OPEX 1	OPEX 2	TCO 1	TCO 2
FCET	258.933	196.707	196.707	0,99	0,99	246.516	173.726	173.726	0,89	0,89
BET	263.694	193.908	193.908	0,99	0,99	256.154	198.120	198.120	1,00	1,00
CNG	173.541	256.034	239.918	1,13	1,07	211.510	260.653	244.538	1,20	1,13
HVO	159.547	207.885	191.770	0,96	0,90	195.832	212.548	196.432	1,02	0,96
e-diesel	159.547	248.077	231.962	1,11	1,05	195.832	253.207	237.092	1,18	1,12
Diesel	159.547	199.006	182.890	0,92	0,86	195.832	203.668	187.553	0,99	0,93

Table 6: CAPEX (€), OPEX (€) and TCO (€/km) for trucks with a 1,000 km daily driving range for 2030 and 2040.

After these initial *Base Case* results a sensitivity analysis was done. In *Case 1* the lowest estimates made by near market sources for battery prices were considered for 2030 and 2040 while the 2023 parameters fully correspond to those of the *Base Case* as there were no significant changes between sources for this year. *Table 7* shows the obtained results for CAPEX and TCO 1&2 from BETs, which are exempted from CO_2 road charges, as these results are the only ones which change compared to the *Base Case*. [7], [8]

Results from Case 1						
	500 km daily driving range		800 km daily driving range		1000 km daily driving range	
	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2
	2023					
BET	358.453	1,41	486.920	1,40	561.503	1,51
	2030					
BET	177.448	0,98	222.243	0,89	254.025	0,98
	2040					
BET	180.510	1,03	213.766	0,90	237.360	0,97

Table 7: Case 1 CAPEX (€) and TCO (€/km) for BETs based on the different daily driving ranges for 2023, 2030 and 2040.

On the contrary, for *Case 2* the Base Case is considered the basis and only the fuel cell system retail price changes based on near market sources, which are the most optimistic ones, for years 2023, 2030 and 2040. *Table 8* shows the obtained results for CAPEX and TCO 1&2 from FCETs, which are exempted from CO_2 road fees, as they are the only ones changing compared to the *Base Case*. [7], [9]

Results from Case 2						
	500 km daily driving range		800 km daily driving range		1000 km daily driving range	
	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2	CAPEX	TCO 1 & 2
	2023					
FCET	348.572	1,80	396.454	1,68	418.685	1,54
	2030					
FCET	206.153	1,22	226.967	1,09	238.860	0,97
	2040					
FCET	198.578	1,13	214.534	0,99	225.171	0,87

Table 8: Case 2 CAPEX (€) and TCO (€/km) for FCETs based on the different daily driving ranges for 2023, 2030 and 2040.

Focussing on *Case 3*, a pessimistic scenario when it comes to diesel prices has been considered, assuming an average diesel retail price of 1.75 €/l excluding VAT for 2023, 2030 and 2040. *Table X9* displays the OPEX_1, OPEX_2, TCO_1 and TCO_2 values obtained for diesel trucks, as for the CAPEX and the other studied technologies nothing changes compared to the *Base Case*. [9]

Result from Case 3												
	500 km daily driving range				800km daily driving range				1000 km daily driving range			
	OPEX 1	OPEX 2	TCO 1	TCO 2	OPEX 1	OPEX 2	TCO 1	TCO 2	OPEX 1	OPEX 2	TCO 1	TCO 2
	2023											
Diesel	165.839	156.298	1,31	1,25	206.769	194.101	1,18	1,12	249.159	233.043	1,09	1,03
	2030											
Diesel	153.407	143.866	1,27	1,21	189.378	176.710	1,13	1,07	226.112	209.996	1,03	0,97
	2040											
Diesel	158.069	148.528	1,38	1,32	194.041	181.373	1,21	1,15	230.775	214.659	1,09	1,03

Table 9: Case 3 OPEX_1, OPEX_2 (€) and TCO_1, TCO_2 (€/km) for diesel trucks based on the different daily driving ranges for 2023, 2030 and 2040.

Referring to *Case 4*, it has been considered that the retail electricity price excluding VAT will decrease for 2030 and 2040 by 25 % and 50 % respectively compared to 2023, where the prices from the *Base Case* for the different daily driving ranges have been maintained. In *Table 10* the OPEX 1 & 2 as well as the TCO 1 & 2 for BETs can be observed. These values for BETs are the only ones changing, as for the CAPEX and the other studied technologies nothing changes compared to the *Base Case*. [10]

Results from Case 4						
	500 km daily driving range		800 km daily driving range		1000 km daily driving range	
	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2
	2023					
BET	119.993	1,41	145.667	1,40	225.571	1,51
	2030					
BET	103.338	0,95	120.980	0,86	171.259	0,90
	2040					
BET	100.538	0,95	115.998	0,84	152.822	0,83

Table 10: Case 4 OPEX 1 & 2 (€) and TCO 1 & 2 (€/km) for BETs based on the different daily driving ranges for 2023, 2030 and 2040.

Finally, for *Case 5*, a 20 % decrease in the at-the-pump hydrogen retail price excluding VAT has been considered compared to the *Base Case* for 2030 and 2040. *Table X11* shows OPEX 1 & 2 as well as the TCO 1 & 2 for FCETs because these values are the only ones changing as for the CAPEX as well as the other studied technologies no parameters are altered compared to the *Base Case*. [9]

Results from Case 5						
	500 km daily driving range		800 km daily driving range		1000 km daily driving range	
	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2	OPEX 1 & 2	TCO 1 & 2
	2023					
FCET	190.601	2,03	245.473	1,85	290.922	1,68
	2030					
FCET	127.947	1,18	154.905	1,04	178.232	0,92
	2040					
FCET	119.311	1,12	141.647	0,97	160.673	0,84

Table 11: Case 5 OPEX 1 & 2 (€) and TCO 1 & 2 (€/km) for FCETs based on the different daily driving ranges for 2023, 2030 and 2040.

Moreover, in *Chapter 5. Discussion*, possible scenarios for the composition of the Spanish trucks' fleet have been given based on the quantity of registered trucks for 2022 and on the TCO results obtained in *Chapter 4. Results* for the *Base Case*. Based on these scenarios the 2023, 2030 and 2040 demand has been predicted and the Spanish dependence on third countries has been assessed. [4], [11], [12], [13], [14], [15], [16], [17], [18], [19]

For 2023 it has been assumed that 99 % of the 5-LH trucks' fleet run on diesel while 0.22% are fully powered by biomethane (bio-CNG) -data from 2022- (*Figure 1*) [11]. Additionally, it has been considered that for this year diesel is made up of 8.5 % of biodiesel [21], [22]. This implies that for 2023 around 123 million kg of biomethane (1,591 GWh) and 65.45 billion litres of diesel, of which 5.56 billion litres are biodiesel are required. [11], [12], [20], [21], [22]

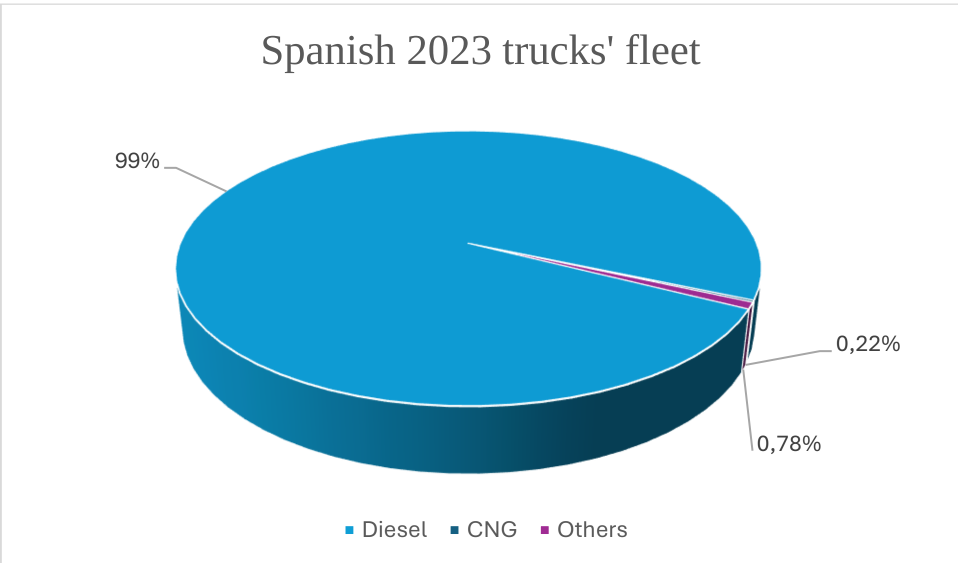

Figure 1: Spanish 5-LH trucks' fleet for 2023 for all daily driving ranges.

For 2030 the trucks' fleet is assumed to be distributed like this for trucks with 500 km and 800 km daily driving ranges: 75 % diesel trucks, 15 % BETs, 8 % HVO trucks and 2 %

CNG trucks, while for trucks with a 1,000 km daily driving range it is assumed to be composed of 85 % diesel trucks, 8 % HVO trucks, 5 % BETs and 2 % CNG trucks (*Figures 2 and 3*).

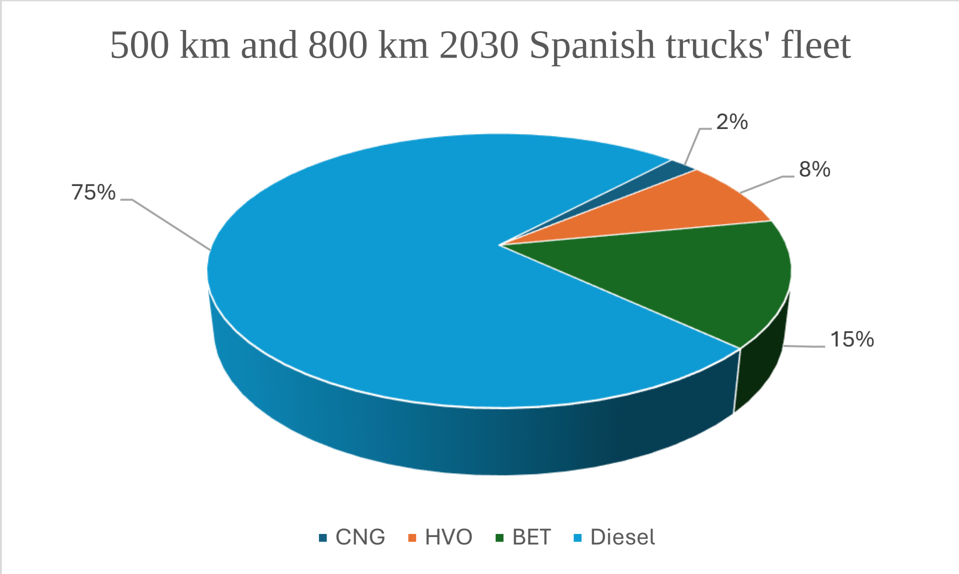

Figure 2: Spanish 5-LH trucks' fleet for 500 km and 800 km daily driving range trucks for 2030.

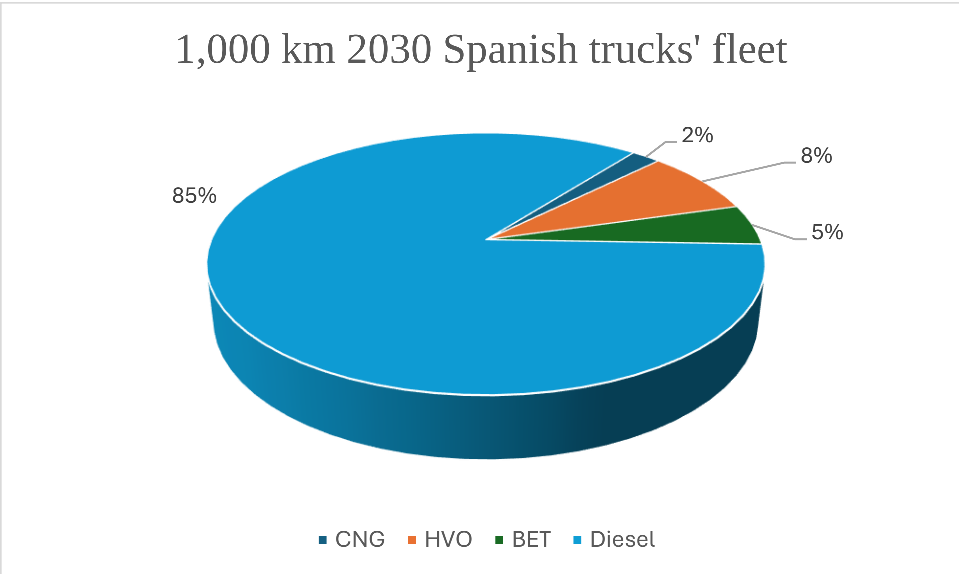

Figure 3: Spanish 5-LH trucks' fleet for 1,000 km daily driving range trucks for 2030.

This implies that the total quantities of fuel needed for 2030 for 5-LH trucks based on the hypothetical scenario proposed are: 880 million kg of biomethane (11,382 GWh), 4 billion litres of HVO, 22,582 GWh for BETs and 39.57 billion litres of diesel of which 3.96 billion litres are biodiesel. [8], [12], [13], [15], [16] For 2040, the trucks' fleet is estimated to be composed of: trucks 50 % diesel trucks, 30% BETs, 14.7 % FCETs, 5 % HVO trucks and 0.3 % CNG for trucks with 500 km and 800 km daily driving ranges, whereas for trucks with 1,000 km daily driving ranges it is estimated to be distributed like this: 77 % diesel trucks, 10 % HVO trucks, 3 % BETs, 0.3% CNG trucks and 9.7 % FCETs (*Figures 4 and 5*).

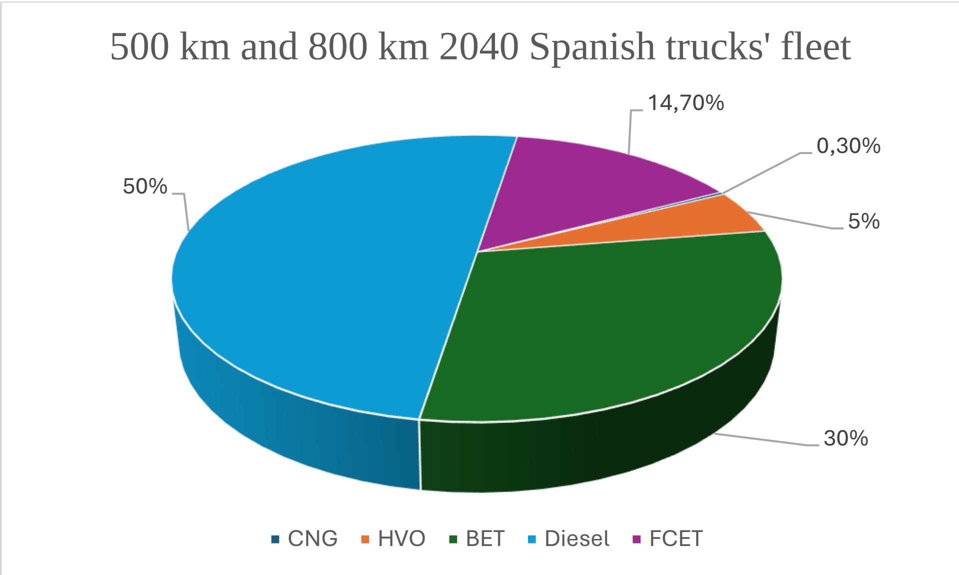

Figure 4: Spanish 5-LH trucks' fleet for 500 km and 800 km daily driving range trucks for 2040.

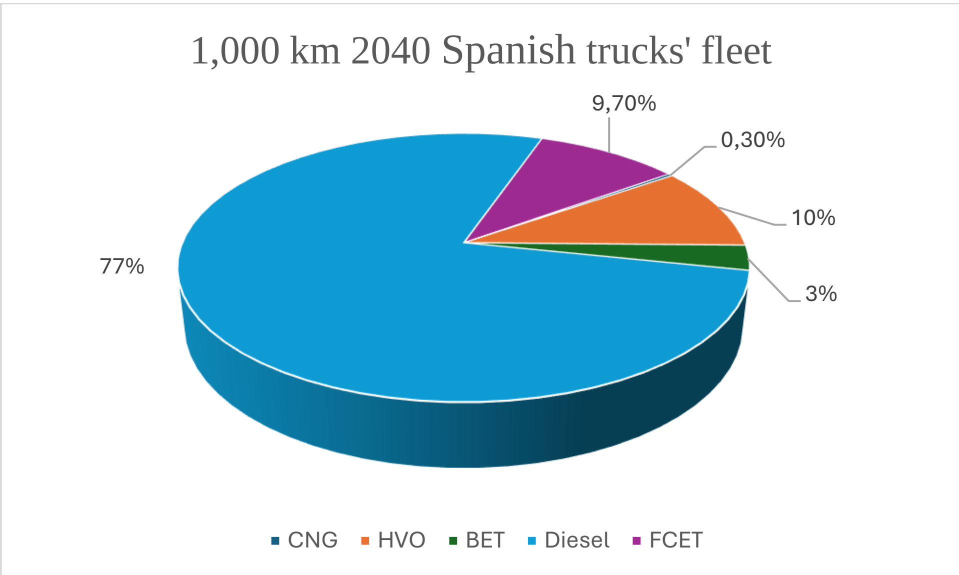

Figure 5: Spanish 5-LH trucks' fleet for 1,000 km daily driving range trucks for 2040.

Therefore, the total quantities of fuel needed for 2040 based on the previous scenario are estimated to be 132 million kg of biomethane (1,708 GWh), 3.55 billion litres of HVO, 38,86 GWh for BETs, 1.6 billion kg of hydrogen and 30.65 billion litres of diesel of which 3.07 billion litres are biodiesel. [8], [17]

Regarding refuelling infrastructure, the current Spanish network has been reviewed for the different technologies, as well as the different European regulations to see if Spain already complies with them currently or, if not, if Spain is likely to comply with them in the short term. [11], [18], [19], [23], [24], [25]

4. CONCLUSIONS

In this project the CAPEX, OPEX and TCO of diesel, e-diesel, HVO, bio-CNG, battery and fuel cell trucks has been computed and analysed for 2023, 2030 and 2040, as well as the Spanish level of dependency on third countries for supplying the Spanish trucks' fleet fuel demand and the available and expected refuelling infrastructures to determine the viability of the different technologies. The main obtained conclusions are the following:

<u>Regarding the CAPEX</u>

- For 2023 FCETs and BETs have the highest CAPEXs, and there is a large gap between them and the retail price of the rest of technologies. However, they are expected to be the technologies with the highest CAPEX reduction for throughout the 2023-2040 period (around 50%).
- Estimated significant retail price reductions of the energy battery -for BETs- and of the fuel cell system -for FCETs- during the 2023-2040 period is mainly what causes these technologies to be more competitive and considerably less affected by inflation for 2030 and 2040.
- Despite this, in 2040 diesel, HVO and e-diesel trucks continue to have the lowest CAPEX for high daily driving ranges (800 km and 1,000 km) due to the large energy battery and the fuel cell sizes they require to be viable. On the contrary, BETs have the lowest CAPEX for 2040 for 500 km daily driving range trucks.
- CNG, diesel, e-diesel and HVO trucks' CAPEXs are expected to increase from 2023 to 2040 mainly due to inflation, as they are considered mature, and therefore, fully developed technologies.

<u>In terms of OPEX and TCO</u>

- For 500 km and 800 km daily driving ranges BETs have the most competitive OPEX during the studied period mainly due to their efficiency and low charging costs as it is considered that they charge 80 % of the times in their deposits.
- However, for 1,000 daily driving range trucks BETs are not as competitive because it is assumed that they mostly charge in public stations, which is considerably more expensive because of higher power charging infrastructure.
- In terms of OPEX and TCO, the best option in the long term to substitute diesel trucks with 1,000 km daily driving ranges is that of FCETs.

Competitiveness in 2030 and 2040

- Bio-CNG and e-diesel trucks are competitive in terms of TCO for 2023 because of their low CAPEXs. However, from 2030 onwards they stop being competitive because their OPEXs continue to be high compared to the rest of technologies. Another reason is that their CAPEXs increase as those of the other mature technologies while FCETs and BETs experience significant CAPEXs reductions.
- It is likely that for 2030 most of the 5-LH trucks are diesel, battery electric or HVO, while for 2040 chances are that the weight of BETs and FCETs considerably increases depending on the daily driving range.
- For 500 km and 800 km daily driving ranges, for 2030 there are TCOs lower than that of diesel (regardless of whether CO_2 road fees are considered), whereas for 1,000 km daily driving ranges diesel has the lowest TCOs until 2040.

Regarding the sensitivity analyses

- Selecting the most optimistic values for BETs' energy batteries, makes BETs even more competitive for 2030 and 2040 for 500 km and 800 km daily driving ranges despite already having the lowest TCO. However, for 1,000 km trucks this optimistic prediction only lowers BETs' TCO enough for them to become the second most competitive technology in 2040 if CO_2 fees are applied, being FCETs the most competitive.
- Optimism in the reduction of the fuel cell system retail price is not enough for FCETs to be better positioned on the TCO rankings except for 1,000 km FCETs, which become the third most competitive technology for 2030.
- For 2040, a diesel retail price of 1,75 €/l excluding VAT implies that BETs, FCETs and HVO become the most competitive technologies.
- Considering a 25 % and a 50 % decrease in the electricity price for 2030 and 2040 compared to that of 2023, BETs become the most competitive technology in terms of TCO for all daily driving ranges for 2040.
- A 20 % decrease in the at-the-pump hydrogen retail price does not imply any changes in the TCOs 2040 rankings for FCETs.

Spanish 2023 fuel dependency on third countries

- For 2023 Spain heavily depends on third non-EU countries for importing crude oil while being partially dependent on EU countries for covering the biodiesel and biomethane expected demand.

Spanish 2030 fuel demand and dependency on third countries

- The expected 2030 fuel demand is of around 11.4 thousand GWh from biomethane, around 4 billion litres of HVO, 22.6 thousand GWh from electricity and 39.57 billion litres of diesel of which 3.96 billion litres are biodiesel (10 %).
- For 2030 Spain is expected to cover around a quarter of the biomethane demand and at least 24.1 % and 26.4 % of the HVO and the biodiesel demand respectively,

probably relying only on other EU countries to cover the remaining part. Moreover, 51.6 % of the total electricity demand is expected to be produced by renewable energy sources, so Spain would only depend on EU and non-EU counties for 48.4 % of the required electricity. Additionally, crude oil is fully imported from third non-EU member states.

Spanish 2040 fuel demand and dependency on third countries

- The expected 2040 fuel demand is of around 1.71 thousand GWh from biomethane, 3,55 billion litres of HVO, 38.86 thousand GWh from electricity, 1,6 billion kg of hydrogen and 30,65 billion litres of diesel of which 3,07 litres are biodiesel (10 %).
- For 2040 Spain is expected to be able to cover about half of the biomethane demand and at least 27.2 %, 20.4 % and 37.8 % of the HVO, biodiesel and hydrogen demands respectively, being the remaining demand supplied by EU countries or countries such as Brazil or Egypt when it comes to green hydrogen. Furthermore, around 80 % of the required electricity is expected to be produced by renewable energy sources for 2040. Finally, crude oil needs to be imported from third non-EU member states.

Spanish refuelling infrastructure

- The Spanish gas stations network complies with the AFIR regulation, so the refuelling infrastructure would not limit the adoption of this technology.
- Spain is currently far from complying with the AFIR regulation in terms of hydrogen stations and chances are that it will not accomplish it by 2030 either, which makes it unlikely for FCETs to increase their market share before 2040 due to the lack of refuelling infrastructure.
- Despite the increase in chargers of a minimum available power of 350 kW, most of the Spanish TEN-T network do not cover the AFIR regulation now. However, for 2030 Spain could manage to comply with this regulation.

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CHAPTER 1. Introduction

1.1. INTRODUCTION

Greenhouse gases (GHGs) linked to domestic transport in the EU represent more than 22% of the total emissions and if the maritime and air sector are taken into account this figure escalates up to 27% [11]. Moreover, road transport in the EU-27 is responsible for 4% of the total $PM_{2.5}$ emissions and for 9% of nitrogen oxide emissions (NO_x). This air pollutant, (NO_x), is especially disturbing as it triggers the formation of secondary $PM_{2.5}$ and O_3 [1].

Long-term exposure to air pollutants has been linked to health problems such as lung cancer, pulmonary disease, chronic respiratory illnesses, heart disease or stroke among others [26]. In 2019, long-term exposure to nitrogen dioxide, fine particulate matter and ozone contributed to 307,000 premature deaths in the EU [1].

In addition to environmental and health problems triggered by the transport sector, it also plays a considerable role in economy. In fact, the transport sector directly employs 10 million workers approximately in the EU and contributes 5% to the European GDP. [2]

In the European continent, road freight is fundamental for trade and commerce. Indeed, 77% of all freight transported over land is carried by trucks and it plays a major role in the supply chain of products which may as well include other means of transportation such as inland waterways, shipping, air and rail transport [27].

From the greenhouse gas emissions caused by road transport in its totality, heavy-duty vehicles are responsible for over 25% of them, which is approximately 6% of the EU's total GHGs emissions. It has also been determined that total road transport GHGs emissions increased by about 5.5% between 2000 and 2019. [27]

This final degree project focuses on studying alternatives towards zero-emission freight transport in Spain. In order to do so the different technologies available for transitioning to zero-emission means of transportation will be studied, particularly focusing on heavy-duty vehicles.

Additionally, research on the infrastructure required to achieve zero-emission freight transport by road will be carried out and its geographical distribution will be displayed depending on the demand in different scenarios.

1.2. STATE OF THE ART

The European Green Deal aims to reduce greenhouse gas emissions from transport by 90% in order to become a climate-neutral economy by 2050 as well as to achieve zero pollution. Additionally, this package of policy initiatives also calls for shifting part of the 75% inland freight carried by road nowadays to rail and inland waterways [2].

In 2019, the European Union approved Regulation (EU) 2019/1242, which requires manufacturers to reduce the CO_2 emissions of new trucks by 15% by 2025 and by 30% by 2030 in comparison to a mid-2019 to mid-2020 baseline). Currently, almost 75% of new trucks are subject to this CO_2 standards.

On 14th February 2023, the European Commission proposed a legislative review to the 2019/1242 Regulation which is even more restrictive towards the CO_2 standards. This new target levels are -45% in 2030, -65% in 2035 and -90% in 2040 (see *Table 1*). After this review, the CO_2 standards have been extended to additional vehicle segments, which implies that more than 98% of the CO_2 emissions coming from the heavy-duty vehicle sector will be regulated. [27].

	2025	2030	2035
Initial Regulation (EU) 2019/1242	15%	30%	-
14th February 2023 legislative review	15%	45%	65%

Table 1. Current CO2 standards targets for new heavy-duty vehicles. [27]

Nowadays, in the European Union there are around 6.2 million trucks and 680.000 buses in circulation whose average age is of 13.9 years old for trucks and 12.8 years old for buses. Additionally, 97.8% of trucks and 94.5% of buses run on diesel which is the traditional and most extended fuelling option for professional transport operators and which was the most affordable option as well before the energy crisis (2022) [28].

A study published on November 2022 [29] that analysed load impacts of electric vehicles (EVs) across 71 potential charging locations determined that these sites form a network that could provide charging access in major highways in Massachusetts and New York such as segments from the I-90 or the I-87.

It was concluded that a typical highway site would require more than 20 fast-chargers to meet the drivers' needs. Moreover, it states that chargers should be brought to the higher capacity power lines that already overlap with the highway system when possible. In the case that a transmission interconnection is needed, which will be highly likely in the next decade for serving light-duty vehicles (LDVs) alone, the grid infrastructure size should be carefully planned thinking in the long term (medium and heavy-duty vehicles' higher electricity demand) in order to reduce the infrastructure costs in the long-run [29].

When it comes to railway transport, the Alternative Fuels Infrastructure Regulation (AFIR) has determined that only around 56% of the existing European rail network is electrified, whereas more than 80% of the total kilometres travelled by train have been done using electricity-powered trains.

Despite the electrification level reached in the railway transport, there are still approximately 6,000 diesel trains operating in the European Union currently. In order to decarbonise them, the available technologies include battery powered trains and hydrogen applications, as the direct electrification of a segment is not reasonable at the moment due to cost-efficiency reasons. [28]

For making ships and planes zero-emissions a possible option could be e-fuels. In case the EU production was fully allocated to these two means of transport, e-fuels could meet almost 6% of the energy demand from the maritime transport sector and 13% of the energy demand from the aviation transport sector by 2035 [30].

According to [26], global road transport CO_2 emissions could be reduced in 73% by 2050 compared to 2020 levels if an accelerated transition to zero-emission vehicles occurs. In case this is achieved for heavy-duty vehicles, the accumulated CO_2 emissions reduction would be of 47.5 billion tonnes between 2020 and 2050.

In order for the transportation sector to fulfil the Paris Agreement, *Table 2* shows that the global share of heavy-duty zero-emission vehicles would need to increase up to 45% by 2030 and to nearly 100% by 2040 in the member countries of the Zero Emission Vehicles Transition Council (ZEVTC). The fastest the transition the better the global health benefits. For example, reaching zero-emissions could avoid 3 million premature deaths through 2050 -$5 trillion in health benefits. [26]

	2025	2030	2035	2040	2045
Bus (>3.5 t.)	7%-30%	75%-90%	90%-100%	100%	100%
Medium truck (3.5-16 t.)	3%-12%	40%-50%	75%-90%	100%	100%
Heavy truck (>16t.)	2%-9%	30%-41%	60%-75%	90%-100%	100%
All HDVs (sales-weighted average per country)	3%-12%	40%-56%	69%-83%	94%-100%	100%

Table 2. Heavy-duty zero-emission vehicles' annual sales shares for ZEVTC countries to align with the Paris Agreement. [26]

Despite this being particularly difficult to achieve currently due to the differences between the total cost of ownership of ICE (internal combustion engine) heavy-duty vehicles and zero-emission vehicles, it has been predicted that in the upcoming years zero-emission trucks will become cheaper because of the emergence of economies of scale due to mass production, which will result into zero-emission trucks having a more competitive price. (See *Figure 1*). [31] [4]

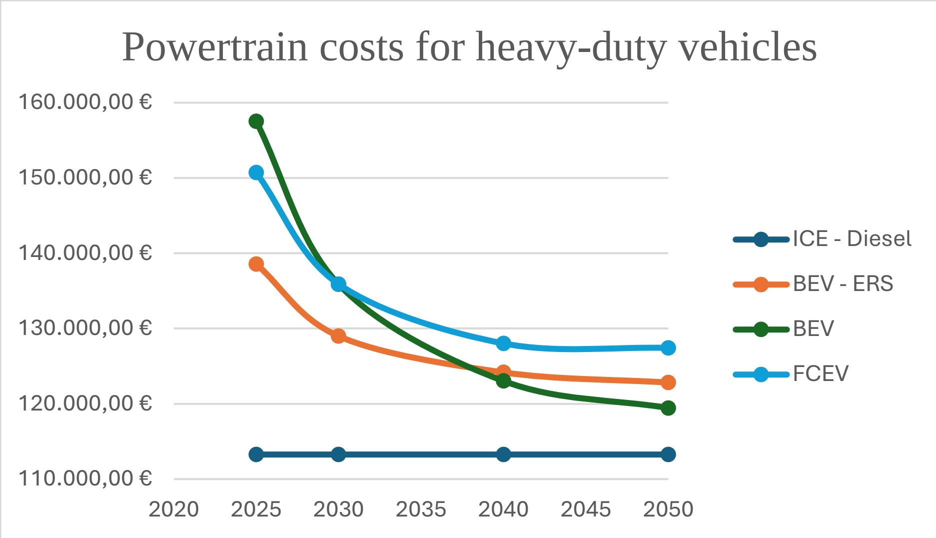

Figure 1. Powertrain costs for heavy-duty vehicles(excluding costs of additional energy efficiency technologies, margins and taxes) (2020). Technologies: ICE (internal combustion engine), BEV (battery electric vehicle -fully electrical), BEV-ERS (BEV vehicles with the required pantograph for drawing charge from the electric road system-ERS) and FCEV (fuel cell electric vehicle). [31]

After explaining the European Union zero-emission freight transport situation it is now time to be more specific about the situation in Spain as this final degree project will focus on this country.

In Spain, between 30-35% of the greenhouse gas emissions of the total emitted by the transportation sectors are caused by heavy-duty vehicles. The greenhouse gas emissions from maritime transport are 3%, 2% of GHGs are emitted by air transport and only 1% of GHGs are caused by railway transport. [11]

Data shows that in 2022, 23% of the buses registered in Spain were compressed natural gas (CNG) vehicles whereas only 9 fuel cell electric buses were registered. When it comes to trucks, most of them are powered by diesel engines and less than 1% uses natural gas. In 2022, registrations of natural gas vehicles (NGV) trucks reached 4.6%. [11]

By using fossil natural gas instead of diesel as fuel, CO_2 emissions are already reduced. However, if the origin of the gas used as fuel in NGV is renewable, this technology can reduce CO_2 emissions between 52% and 235% depending on the waste used to produce the biomethane. This biofuel is produced by “upgrading” the biogas, which, as a consequence of manure management credits, can reduce GHGs emissions by over 100 % according to the RED II EU Directive. [11]

In Spain, for 2023 there were accounted 131 gas stations which can provide CNG and 91 gas stations which can supply LNG. Moreover, most of the stations have the capacity to provide CNG as well as LNG. Additionally, there are 33 new gas stations planned. Currently, having such an extended network of natural gas stations will likely enhance a fast penetration of biomethane in the transport sector. In 2022, only 4% of the total biomethane produced -296 GWh- was used in the domestic transport sector. [11]

Focussing on biomethane production, there are currently 8 commercial plants capable of producing 349 GWh/year -injected in the natural gas network- and 13 pilot plants with a capacity production of 22.86 GWh/year intended to nurture the transport sector.

On the contrary, there are only 9 hydrogen stations currently operating in Spain, which is far from the objectives settled in the European legislation -between 100 and 150 hydrogen stations by 2030.

Talking about renewable hydrogen production in Spain, there are around 100 hydrogen production projects in preliminary stages. If developed, the accumulated electrolysis power would increase to 18.1 GW and a third of the production would be intended for the transportation sector.

In the case of heavy-duty vehicles, their autonomy varies from 150 km to 400 km with the exception of the Tesla Semi -800 km- which is not available yet. For FCEV, the current maximum autonomy is 400 km, although this figure is expected to increase up to 1200 km. [11]

The total cost of ownership (TCO) in the case of heavy-duty LNG vehicles is 10% higher than its diesel counterpart. The TCO of biomethane would be at least a 100% higher in comparison to a diesel heavy-duty vehicle and for hydrogen technologies the TCO would be 65%-100% higher than TCO of diesel ones. [11]

When it comes to shipping, LNG technology would be an immediate transition towards decarbonizing this sector. Ships powered by methanol and hydrogen have also started being ordered (51 and 8 respectively). Spain is leader in bunkering LNG infrastructure, which is available in 19 ports.

When it comes to railway transport, Spanish infrastructure is highly electrified, so in the case of not electrified segments instead of using diesel trains such as in other European countries, it would be more convenient the use of hybrid trains such as the Alvia S-730 model, currently operating in the Madrid-Galicia journey.

Figures 2 and 3 graphically shows the Spanish road freight transport fleet in 2022 that is made up by 65 523 buses and 2 474 451 trucks in total.

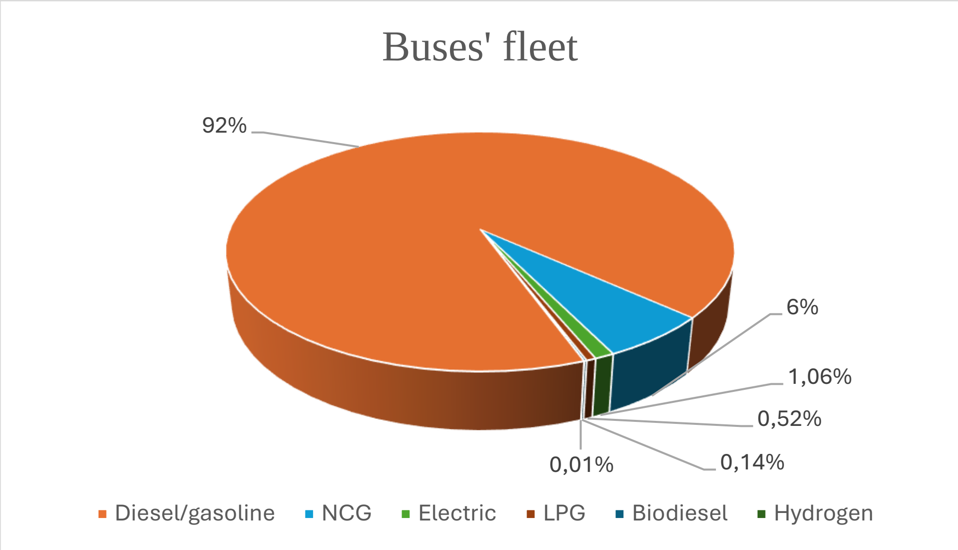

Figure 2. Spanish buses' fleet in 2022. [11]

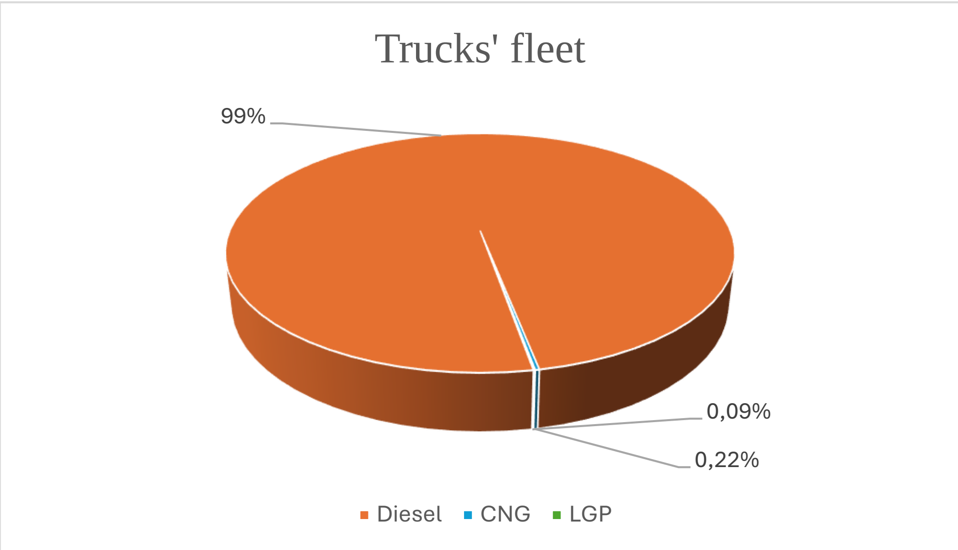

Figure 3. Spanish trucks' fleet in 2022. [11]

1.3. MOTIVATION

As road freight transport plays a key role in economic growth as well as in the current environmental issues -due to the greenhouse gas emissions it produces- and in population's health -due to the air pollution caused by $PM_{2.5}$, NO_x and O_3 emissions- the European Union has been since the late 20th century proposing and approving regulations to achieve a climate-neutral economy, which includes heavy-duty zero-emission vehicles.

In order to achieve so, many experts from a wide range of fields are working together to transition from traditional combustion engines to alternatively powered vehicles that align with the European targets. A particularly arduous task is achieving zero-emissions freight transport -a fundamental piece of the supply chain of the vast majority of the manufactured products- as the means of transportation used carry considerable amounts of weight through long distances.

Having been working for the OVEMS (Observatorio del Vehículo Eléctrico y Movilidad Sostenible, an observatory from Comillas University Technological Research Institute) since January 2023, I decided to do the final degree project about the study of alternatives for the transition towards zero-emission freight transport in Spain as I found it a really interesting topic thinking in both ways, as an engineer and as someone who also studies Business Administration as renewing the ships, trains and heavy-duty vehicles so that they are zero-emissions is something costly that will definitely have an impact on the economy and general welfare.

Moreover, I also believe that this project will also serve as a starting point for creating a new chapter in the OVEMS that focuses on freight transport vehicles, as currently the focus is mainly set on light-duty vehicles and their impact on mobility.

1.4. OBJECTIVES

Reducing transport emissions is currently one of the main key challenges in our society. Aligned with this major objective this final degree project has as main goals the following:

- Characterize technological alternatives for achieving zero emissions in road freight transport carried out by trucks. Technological and economic characteristics will be provided for the different current and alternative technologies.
- Establish the energetic vector for each of the previously mentioned technologies and whether Spain would be dependent on third countries based on the different energy sources.
- Quantify the demand and estimate the required infrastructure as a guideline based on different scenarios.

CHAPTER 2. Description of the studied fleet

This project is focused on studying the alternatives for the transition towards zero-emission freight transport in Spain. More precisely, the segment of the road transport fleet that will be analysed are the trucks belonging to the 5-LH groups according to the VECTO (Vehicle Energy Consumption calculation Tool) category. The tool calculation referred to in the VECTO acronym consists of a simulation by the European Commission which is used for estimating the fuel consumption and the CO_2 emissions of HDVs (High Duty Vehicles). [4], [5]

The 5-LH VECTO category consists of long-haul tractor trailers which weight more than 16 tones, have a 350 kW power unit rating and are composed of a 4x2 axis and a tractor chassis. This category has been selected for this analysis as it has the biggest market share among the VECTO categories (60.9% market share in 2020 and 48% market share in 2022). [4], [5]

The 5-LH group is subdivided into three categories based on its daily driving range, which will be taken into consideration for this report. These subcategories are the following: [4]

- <u>Daily driving range of up to 500 km</u>: these trucks are expected to return to their deposits after finishing their daily operations.
- <u>Daily driving range of up to 800 km</u>: in this case, trucks may or may not return to their deposits after finishing their daily operations, depending on the route of the particular truck, which may or may not involve crossing borders.
- <u>Daily driving range of 1,000 km</u>: it includes trucks whose routes cross borders, and therefore, they are not expected to return to their deposits after their daily operations.

Traditionally, the truck fleet has been composed of diesel truck, yet due to the implementation of new European Directives in order to achieve sustainability in the near future new technologies have been developed. The following sections will summarize each of the technologies studied in this report (diesel, e-diesel, HVO, CNG, FCET and BET).

2.1. DIESEL, E-DIESEL AND HVO TRUCKS

Diesel, e-diesel and HVO (Hydrotreated Vegetable Oil) trucks have the same powertrain, yet the fuel consumed by each of them changes. *Figure 4* shows a simplified scheme of the diesel, e-diesel or HVO powertrain.

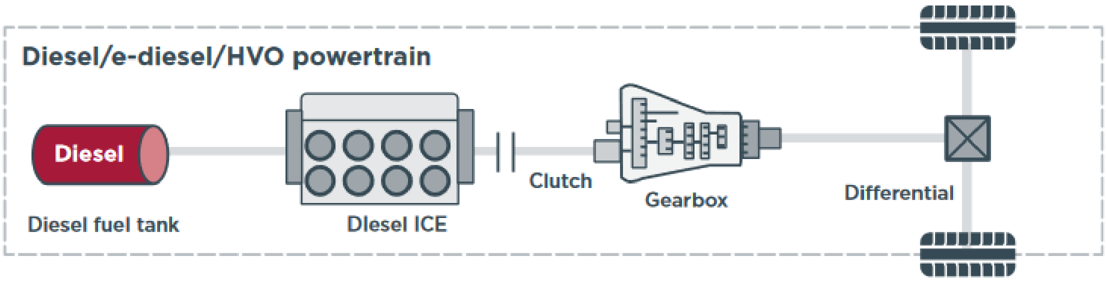

Figure 4. Truck's powertrain for diesel, e-diesel and HVO technologies. [4]

The e-diesel and the HVO trucks have lower CO_2 total emissions ("well-to-wheel") in comparison to the traditional diesel truck. This is because of how e-diesel and HVO fuels are produced.

E-diesel, a type of e-fuel, is produced using hydrogen and CO_2. Although this technology emits CO_2 during the internal combustion that takes place in the truck's ICE (Internal Combustion Engine), it could be considered climate-neutral if the hydrogen used in its production is certified as "green hydrogen", if the CO_2 is directly captured from the atmosphere and if the stages of transport and distribution are completely decarbonised. [30]

For the e-diesel, the EU is currently considering two different sourcing possibilities: Concentrated Point Source (CPS) and Direct Air Capture (DAC). The last one involves more expensive technology as well as energy-intensive processes when compared to CPS, yet it is estimated that its implementation will be required in the future (from 2040 onwards) as CO_2 capture from CPS has a limited supply. [4]

According to [30], by 2035, the road transport demand of e-fuels is expected to be around two-thirds of the total European production. If this fraction of the production was exclusively for supplying trucks, e-fuels would be capable of meeting the demand of 315,000 LH trucks, which represents 5.6 % of total trucks in the EU in 2035. Although e-fuels could be imported, the imports of e-diesel are unlikely to be enough to cover the remaining demand. The positive side is that e-diesel could be used in diesel trucks without making any adjustment, which would speed up the decarbonization of this means of transport.

Due to all of this, it seems difficult to rely solely on e-diesel trucks to decarbonize freight transport in the near future. However, e-fuels are a reasonable potential solution for decarbonizing other means of transportation, such as marine and air transport, in which electrification or the use of hydrogen is not a possible solution. [30]

HVO is a type of biofuel produced using as raw materials waste products like used cooking oil and fats from the food industry, which is the low-GHG HVO, or vegetable oils such as palm and soy oil, which are related to high GHG emissions as well as noticeable emissions derived from changing the land use. Moreover, biofuels can be linked to food and biodiversity damage as well as to a factor that worsens climate change. [4], [30], [32]

An important advantage of HVO is that it can reduce CO_2 well-to-wheel emissions by up to 90% in comparison to a diesel truck. Moreover, this fuel can be used in diesel trucks without making any adjustment. Some manufacturers who offer this alternative technology guarantee an equal performance as well as the same service intervals (around 200,000 km for long-haul trucks) as for diesel trucks. [32]

Despite these major advantages, if the main objective is to achieve sustainable road transport, it is required that the biomass used for producing HVO comes from a sustainable source, which will lead to a considerable reduction in the quantities of HVO and other advanced biofuels produced. Therefore, some authors agree on reserving biofuels for means of transportation that cannot be electrified or in which the use of hydrogen is not possible. [30]

2.2. COMPRESSED NATURAL GAS (CNG) TRUCKS

Compressed Natural Gas trucks are an alternative to conventional diesel trucks. Natural gas is a fossil fuel composed on its majority by methane, which is the cleanest burning fuel when it comes to NO_x and PM emissions, which, as previously explained, are pollutants that can have a serious impact on our health. [33]

CNG trucks' way of working is similar to that of gasoline-powered vehicles as most of the Heavy-Duty Vehicles (HDVs) running on natural gas use spark-ignited systems in which the engine functions exactly the same way as gasoline internal combustion engines do. [34]

The natural gas at a high-pressure stored in multiple fuel tanks, generally at the back of the driver's cabin, is transferred from the fuel tanks to the combustion chamber, but first, it needs to go through the fuel lines, in which a pressure regulator is placed, in order to reduce the pressure level of the natural gas so that it is compatible with the engine fuel injection system. [34]

Figure 5 shows a simplified scheme of the CNG trucks' powertrain. [4]

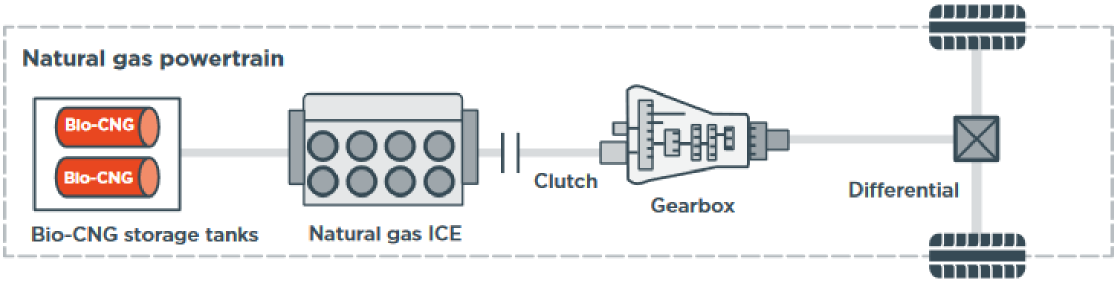

Figure 5. Simplified scheme of the powertrain for compressed natural gas trucks. [4]

CNG trucks can use natural gas as fuel, which is not the most sustainable alternative, or biogas, biomethane to be more precise, which in the European Union is produced in general terms using silage maize as the main raw material. This way of producing biogas is not considered a low-GHG process, as maize is linked to emissions due to land change. [4]

However, the production of bio-CNG (low-GHG biomethane) is possible if agricultural and livestock waste and domestic and industrial organic waste are used, as well as waste coming from wastewater treatment plants and dumps. [11]

In Spain, there are currently eight production plants of biomethane with a production capacity of 349 GWh/year, which is expected to increase to 3,700 GWh/year by 2025. The biggest biomethane production plant (180 GWh/year) is located in Valdemingómez and it uses organic material and gases coming from domestic waste stored in the dump in this location. [11]

Moreover, Spain has been estimated to have a potential biomethane production that escalates to 163 TWh/year for 2023, of which only around 0.16 % is used. In addition, Spain and Portugal had a total of 170 gas stations in 2023 and 33 additional gas stations planned, which shows that the transition to CNG trucks powered by biomethane would be fast in the Iberian Peninsula. [11]

2.3. BATTERY ELECTRIC TRUCKS (BET)

5-LH trucks represent a big challenge for electrification due to the large daily distance that these vehicles are required to cover. Therefore, although battery electric trucks (BETs) are one of the best ways of decarbonizing road freight transport, as they are considered zero-emission vehicles, research is still needed to improve several components of these trucks, such as the electric battery and their autonomy. [8]

For example, BET energy consumption, which in 2020 was estimated at 1.38 kWh/km, is expected to plummet to 0.99 kWh/km by 2030 which is a 26% decrease. This implies that the battery energy capacity required to meet the minimum single charge range of 500 km will decrease from 930 kWh in 2020 to 675 kWh by 2030. [8]

There are several types of batteries based on the materials used. The Lithium-ion (Li-ion) battery, which is the most common and considered in this report, has higher energy density than other battery systems. [35]

Battery density is a key parameter as the maximum transported payload and volume for a given distance directly depends on it. Battery duration also plays a key role when choosing between different batteries. These characteristics depend on the cathode and the anode materials, the electrolyte and the cells' size and shape, among other factors. [35]

Additionally, it has been analysed if the driving range of the battery electric truck can be altered due to extreme conditions as a result of the thermal needs present in these vehicles, which is a major concern for long-haul trucks. For example, when comparing the driving range at an ambient temperature of 15ºC (base case) and ambient temperatures of -7ºC and 35ºC (extreme cases), it has been checked that the reduction of the driving ranges is equal to or lower than 9 % (the bigger the battery size, the bigger the reduction). [35]

Currently, the most important design parameter for achieving high durability and energy density is the cathode of the Li-ion battery. The three most popular Li-ion cathode chemistries are Lithium Nickel Manganese Cobalt Oxide (NMC) -which is the most spread battery technology as it is present in more than 28% of global electric vehicles and its market share is estimated to reach 63% by 2027-, Lithium Nickel Cobalt Aluminium Oxide (NCA) -which is similar to the NMC technology in terms of parameters but is less competitive in price-, and the Lithium Iron Phosphate (LPF) -which has lower energy density than NCA and NMC technologies but offers a higher life cycle-. [35]

When it comes to electric motor technology, there are two different types: Asynchronous Induction Motors (ASM) -whose manufacturing cost is lower, but its motor control is more difficult- and Permanent Magnet Synchronous Motors (PMSM) -which have higher manufacturing costs but offer a more compact mechanical design and higher efficiency. [35]

A simplified explanation of how BETs work would be the following: when being pressed, the accelerator sends a software signal to the power inverter or converter, which converts the direct current (DC) stored in the battery into alternating current (AC) that enters the electric motor, where the electrical energy is converted into mechanical energy. Then, a set of gears, which are placed downstream from the motor, enables the reduction of the electric motor's speed and consequently the increase of the torque applied to the truck's wheels. [36], [37], [38]

Figure 6 shows a simplified scheme of the powertrain of a battery electric truck. [4]

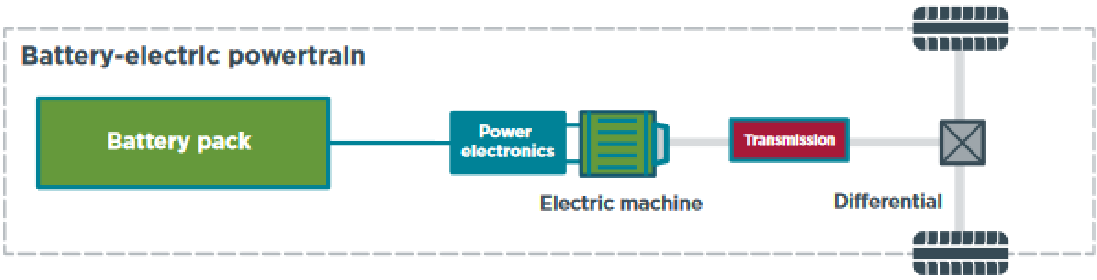

Figure 6. Simplified scheme for the battery electric truck powertrain. [4]

Another important feature in battery electric trucks is regenerative braking, which is a mechanism that converts kinetic energy into electrical energy during the braking process, as the electric motor acts as a generator. This energy is stored at the battery pack for later use, which improves the truck's energy efficiency. [37], [38]

2.4. FUEL CELL ELECTRIC TRUCKS (FCET)

Fuel cell electric trucks (FCETs) are hybrid vehicles which have power batteries and hydrogen storage tanks as energy storage systems and elements such as fuel cells and electric motors as energy conversion devices, among others. This type of trucks are also considered zero-emission vehicles. [39]

Fuel cell powertrains need more complex designs and power strategies in comparison to battery electric powertrains. Based on the size of the powertrain components, the fuel cell powertrains can be classified into a load follower or a range-extended fuel cell battery hybrid powertrain. [39]

The load follower fuel cell powertrain is composed of a fuel cell stack that provides most of the power and a small power battery that provides extra electric power when a peak demand occurs. It is not common to have a pure fuel cell powertrain -which implies no power battery- because it would need oversized fuel cell stacks and the regenerative braking opportunity is lost. [39]

The range-extended fuel cell powertrain is mainly powered by a battery and a small fuel cell unit, which provides additional extended driving range and offers the possibility to recharge the battery pack as it has a DC charging socket. [39]

Fuel cell powertrains offer five different modes of operation: the electric motor can be directly powered by the fuel cell stack, the fuel cell stack can power the electric motor and charge the battery at the same time, the electric motor can be directly powered by the electric battery, the maximum power can be achieved by combining the battery and the fuel cell stack power or the regenerative braking mode, in which the electric motor transforms into a generator. [39]

Figure 7 shows the simplified scheme of the fuel cell electric truck powertrain. [4]

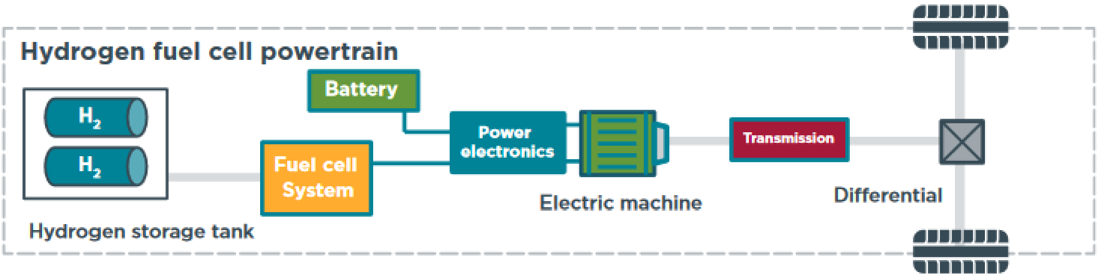

Figure 7. Simplified scheme of the fuel cell electric truck powertrain. [4]

The hydrogen storage system is one of the key components in the FCETs and its technologies are currently being developed. The most extended hydrogen tank is the one of compressed hydrogen at 350 bar, although the newest tanks are working at 700 bar and the current refuelling infrastructure is being adapted so that it can supply hydrogen at this pressure. [11], [39]

For the type of trucks studied in this report (5-LH), the tank volume is limited by packaging restrictions. With a 350 bar tank the maximum driving range that the truck could reach with the current technology would be 400 km due to the low volumetric density (16 g H_2) of this hydrogen storage system, which is not enough if considering that for 5-LH trucks the daily driving ranges are between 500 and 1,000 km. [39]

Hydrogen tanks of 700 bar would provide a higher volumetric density (27 g H_2), which translates into a higher driving range, a key parameter for long-haul trucks. Therefore, this study will focus on 700 bar FCETs. The only two hydrogen storage systems that have reached the stage of technological and refuelling supply readiness are the 700 bar and 350 bar tanks. [39]

A hydrogen storage system that is currently being developed is the liquid H_2 or cryogenic hydrogen storage for which temperatures of -253 ºC are required. This technology offers a higher volumetric density (more than 36 g H_2). There is evidence that cryogenic hydrogen storage tanks are less expensive than compressed tanks as it can be observed in *Table 3*. [39]

Cryo-compressed hydrogen, another storage system that is being developed, combines compressed gas (300 bar) and liquid hydrogen, which is stored at temperatures that vary from -150 ºC to -240 ºC. This allows to achieve a higher volumetric density (more than 40 g H_2), lower production costs, less weight and better safety. The cost of this technology compared to the cost pf a 350 bar hydrogen storage tank can be seen in *Table 3*. [39]

Hydrogen storage systems' technical specifications				
	350 bar H2	**700 bar H2**	**Liquid H2**	**Cryo-compressed H2**
Volumetric density (g/l)	16	27	36	40
Cost	Reference	10%	-35%	-
Hydrogen storage system technology readiness level	8-9	8-9	4-6	-
Hydrogen refuelling supply technology readiness level	8-9	8-9	2-4	1-3

Table 3. Hydrogen storage systems' specifications. The technology readiness follows the following criteria: 1-observation, 2-formulation, 3-experimentation, 4-lab validation, 5-industrial validation, 6-technical demonstration, 7-prototyping, 8-qualification and 9-commercialization. [39]

As it can be observed in *Table 3*, the cryo-compressed hydrogen system is the least developed technology, although it is the one with the highest volumetric density. The 350 bar and 700 bar technologies are the only ones that are ready. Although the 350 bar technology is slightly less expensive, the 700 bar technology provides approximately twice the volumetric density. The liquid H_2 system, despite being the cheapest one and providing a high volumetric density, is still between the lab validation and the technical demonstration phases. It will take several years and a considerable capital investment for this technology to be ready. [39]

CHAPTER 3. TCO calculation

The TCO refers to the total cost of ownership per kilometre (€/km). In order to compute it the following values are required: the CAPEX in euros, the OPEX in euros, the subsidies (SUB) provided by the government on the initial purchase in euros, the scrappage value (SV) in euros, the considered lifetime of the vehicle (N) which will be 5 years in this report and the capital recovery factor (CRF) for which the discount rate value (i) needs to be established -it will be 9.5% for this report-, and the annual kilometres travelled (AKT). [6]

The following formulas show how to compute the CRF and the TCO:

$$CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1}$$

$$TCO = \frac{\left(CAPEX - SUB - \frac{SV}{(1+i)^N}\right) \cdot CRF + \frac{1}{N} \cdot \sum_{n=1}^{N} \frac{OPEX}{(1+i)^n}}{AKT}$$

With the selected initial parameters in terms of lifetime (5 years) and discount rate (9.5%), the obtained CRF applying the previous formula is 0.2604.

3.1. CAPEX CALCULATION

The CAPEX can be subdivided into three parameters: powertrain, energy storage and rest of the truck. The powertrain refers to the truck's power source (combustion engine, fuel cell or motor), any auxiliar components required for operation and the transmission along with the gearbox or the electric drive. The energy storage parameter refers to costs exclusively related to fuel tanks or batteries, which are the energy source of the vehicle. The rest of the truck components includes costs related to the vehicle glider among others. [6]

$$CAPEX = Powertrain + energy\ storage + rest\ of\ the\ truck$$

3.1.1. POWERTRAIN

3.1.1.1. TRANSMISSION AND GEARBOX/ELECTRIC DRIVE

3.1.1.1.1. Automated transmission and gearbox for diesel, e-diesel, HVO and bio-CNG 5-LH trucks

According to [6], the average automated transmission of a high-duty truck (HDT) had a direct cost of €5,322.81 per truck in 2019. Considering that the Spanish inflation rate from 2019 to 2023 was 15.32% [40] (with €1 in 2019 it could be purchased the same as with €1.1532 in 2023), the 2023 average direct manufacturing cost of the automated transmission for HDTs was €6,138,26.

However, for long-haul tractor trailers with a 4x2 axel and tractor chassis the automated transmission direct manufacturing cost is slightly above according to several web pages specialized on it after discounting a percentage related to indirect costs. Therefore, the direct manufacturing cost of the automated transmission for further calculations will be established at €7,700. [41]

Talking about the truck's 12 speed gearbox, after looking in several second-hand web pages and discounting a percentage due to indirect costs and the usage that the component being sold already has, it has been estimated that the direct manufacturing cost of the gearbox is around €17,000, which is the value that will be used for further calculations in this report. [42]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, which are higher than this target, an annual inflation rate of 2.5% will be used for calculating the average transmission and gearbox direct cost for 2030 and 2040 (*Table 4*). [43]

Direct manufacturing cost of the automated transmission and gearbox (€)			
	2023	**2030**	**2040**
Automated transmission	7.700,00	9.152,88	11.716,46
Gearbox	17.000,00	20.207,66	25.867,51

Table 4. Direct manufacturing costs of the automated transmission and the gearbox in € for 2023, 2030 and 2040. [6], [41], [42], [43]

In order to estimate the retail price, the manufacturing cost shown on *Table 4* will be increased by 36%, which is the Indirect Cost Multiplier (ICM) applied to diesel, e-diesel, HVO and CNG technologies [5], [6]. The following table shows the retail price values that will be used in this report for calculating the CAPEX and the TCO (*Table 5*).

Retail price of the automated transmission and gearbox (€)			
	2023	2030	2040
Automated transmission	10.472,00	12.447,92	15.934,39
Gearbox	23.120,00	27.482,41	35.179,81

Table 5. Retail price of the automated transmission and the gearbox in € for 2023, 2030 and 2040. [5], [6], [40], [41], [42], [43]

3.1.1.1.2. Electric drive for FCET and BET 5-LH trucks

The electric drive is a key component in FECTs and BETs as it transforms the electrical energy coming from the electric battery in BETs or the fuel cell system in FCETs into mechanical energy and transmits it into motion. [36]

The electric drive is composed of and electric motor (an AC motor), a set of gears located downstream the motor capable of reducing the electric motor's speed, which increases the torque applied to the truck's wheels, and an inverter placed upstream the motor that, by converting the frequency and amplitude provided by the power supply system, enables the direction of rotation and its speed to be modified. [36], [44]

Tables 6, 7 and *8* show different manufacturing costs in €/kW for the electric drive for different years. As it can be observed, the electric drive cost changes depending on the source, although all figures have the same order of magnitude when comparing them.

Direct manufacturing cost of the electric drive (€/kW)			
Component	2023	2030	2040
Electric drive (€/kW)	58	22	17

Table 6. Direct manufacturing cost of the electric drive in €/kW for 2023, 2030 and 2040 periods. [4]

Direct manufacturing cost of the electric drive (€/kW)			
Component	2022	2025	2030
Electric drive (€/kW)	52	29	15

Table 7. Direct manufacturing cost of the electric drive in €/kW for 2022, 2025 and 2030 periods. [44]

Direct manufacturing cost of the electric drive (€/kW)			
Component	2022	2030	2040
Electric drive (€/kW)	58	17	14

Table 8. Direct manufacturing cost of the electric drive in €/kW for 2022, 2030 and 2040 periods. [5]

For the 2022-2023 period the values are very similar, no matter the source. As most authors agree on a direct manufacturing cost of €58 per kW for the electric drive, this will be the selected value.

For 2030, different estimates suggest a cost between €15 and €22 per kW. As authors do not agree on a common value the direct manufacturing cost used for 2030 will be the average of the proposed values: €18 per kW. [4], [5], [44]

For 2040 it has been estimated that the direct manufacturing cost of the electric drive is between €14 and €17 per kW. For this period the average will also be computed, resulting in a cost of €15.5 per kW. [5], [44]

Table 9 shows a summary of the direct manufacturing cost of the electric driver in €/kW for 2023, 2030 and 2040 that will be used in this report for future calculations.

Direct manufacturing cost of the electric drive (€/kW)			
Component	**2023**	**2030**	**2040**
Electric drive (€/kW)	58	18	15,5

Table 9. Selected direct manufacturing cost of the electric drive in €/kW for 2023, 2030 and 2040. [4], [5], [44]

The electric drive specification for battery-electric and fuel cell 5-LH trucks is 350 kW [39]. Considering this, the total direct manufacturing cost of the electric drive in € for 2023, 2030 and 2040 has been calculated and is shown in *Table 10*.

Direct manufacturing cost of the electric drive (€)			
Component	**2023**	**2030**	**2040**
Electric drive (€)	20.300,00	6.300,00	5.425,00

Table 10. Total direct manufacturing cost of the electric drive in € for 2023, 2030 and 2040. [4], [5], [44]

This shows the direct manufacturing cost of the electric drive. For estimating the retail price, based on the literature a cost multiplier of 1.36 will be applied [5], [6], [8], [45]. For this component inflation is not considered to be a key factor when determining the price for the following decades as its technological development is what will influence the most its price. The following table (*Table 11*) shows the retail price of the electric drive in € for 2023, 2030 and 2040:

Retail price of the electric drive (€)			
Component	**2023**	**2030**	**2040**
Electric drive (€)	27.608,00	8.568,00	7.378,00

Table 11. Retail price of the electric drive in € for 2023, 2030 and 2040. [4], [5], [6], [8], [44], [45]

3.1.1.2. COMBUSTION ENGINE OR FUEL CELL

3.1.1.2.1. Diesel and Natural Gas (NG) engines

According to [6], the diesel engine direct manufacturing cost in 2019 was between €39.50 per kW and €41.90 per kW, being 40.77 €/kW the most likely value. Taking into account that the Spanish inflation between 2019 and 2023 was 15.32% [40], the diesel engine cost is currently between €45.55 and €48.32 per kW, with 47.02 €/kW as the most likely value *(Table 12)*.

The diesel engine is the same engine as the one used in e-diesel and HVO trucks and therefore the three of them have the same direct manufacturing cost. [4], [5], [31], [32], [44]

The Natural Gas (NG) engine manufacturing cost in 2019 was between €31.88 per kW and €39.50 per kW, with 32.87 €/kW as the most likely value. Considering the Spanish inflation rate between 2019 and 2023 (€1 in 2019 has the same value as €1.1532 in 2023 [40]), the NG engine cost is currently between €36.76 and €45.55 per kW, being 37.91 €/kW the most likely value (*Table 12*). [6]

Diesel and NG engine direct manufacturing cost (€/kW)			
	Low	High	Most likely
Diesel/e-diesel/HVO engine	45,55	48,32	47,02
NG engine	36,76	45,55	37,91

Table 12. 2023 diesel, e-diesel, HVO and NG engine direct manufacturing cost in €/kW. [6], [40]

In most of the reviewed literature the selected power unit rating for the 5-LH truck's category is 350 kW, which matches with the definition of the 5-LH VECTO group. Therefore, this will be the value used for calculating the diesel and NG engine direct manufacturing cost in euros, which is assumed to change during the following decades depending on the inflation rate for this report. (*Table 13*). [4], [6], [31], [40]

Diesel and NG engine direct manufacturing cost (€)			
	Low	High	Most likely
Diesel/e-diesel/HVO engine	15.942,99	16.911,68	16.455,59
NG engine	12.867,41	15.942,99	13.266,99

Table 13. 2023 diesel, e-diesel, HVO and NG engine direct manufacturing cost for 5-LH trucks with 350 kW as power unit rating in € for year 2023. [4], [6], [31], [40]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, an annual inflation rate of 2.5% will be assumed for estimating the diesel and NG engine direct manufacturing cost for years 2030 and 2040 (*Table 14*). [43]

Diesel and NG engine direct manufacturing cost (€)						
	Low		High		Most likely	
	2030	2040	2030	2040	2030	2040
Diesel/e-diesel/HVO engine	18.951,21	24.259,14	20.102,67	25.733,12	19.560,52	25.039,12
NG engine	15.295,30	19.579,28	18.951,21	24.259,14	15.770,28	20.187,29

Table 14. Diesel, e-diesel, HVO and NG engine direct manufacturing costs in € for 2030 and 2040. [6], [40], [43]

The selected engine direct manufacturing costs in this report for diesel, e-diesel and HVO technologies will be the most likely ones, whereas for NG technologies it will be the highest one (otherwise the engine costs do not match with the research done). For estimating the CAPEX and the TCO in this report, the input needed is the retail price. Therefore, the engine direct manufacturing cost selected will be multiplied by 1.36, which is the estimated indirect cost multiplier for these technologies [5], [6], [45]. The following tables shows a summary of these figures *(Table 15)*:

Diesel and NG engine established retail price (€)			
	2023	2030	2040
Diesel engine	22.379,60	26.602,31	34.053,21
NG engine	21.682,47	25.773,64	32.992,44

Table 15. Diesel, e-diesel, HVO and NG engine established retail price in € for 2023, 2030 and 2040. [5], [6], [43], [45]

3.1.1.2.2. FCET fuel cell systems and power battery and FCET and BET power electronics

FCET power source is composed of the fuel cell system, the power battery and the power electronics, which is the same as for BETs. Before estimating the cost of each of these parts it is needed to establish the specifications of the fuel cell system and the battery pack.

For the FCET belonging to the 5-LH category the specification of the fuel cell unit power varies from 180 to 210 kW as it can be seen in *Tables 16* and *17*. In this report, the specification for the fuel cell system will be 180 kW as it is the most repeated value in the literature reviewed. [5], [39], [44], [45]

When it comes to battery size specifications for 5-LH FCET, it varies from 70 to 72 kWh as it is shown in *Tables 16* and *17*. As most of the authors agree on a 72 kWh battery size, this will be the value selected for doing future calculations on this report. [5], [39], [44], [45]

FCET main specifications for fuel cell system and battery pack		
	Fuel cell unit power (kW)	Battery size (kWh)
5-LH	210	70

Table 16. FCET specifications for the fuel cell system and the battery pack. [5]

FCET main specifications for fuel cell system and battery pack		
	Fuel cell unit power (kW)	Battery size (kWh)
5-LH	180	72

Table 17. FCET specifications for the fuel cell system and the battery pack selected for this report. [39], [44], [45]

<u>Fuel cell unit direct manufacturing costs</u>

The direct manufacturing costs of the fuel cell stack are currently between €145 and €1,040 per kW for FECTs from the 5-LH VECTO category. As it can be observed in *Tables 18, 19* and 20, the average of this range (460 €/kW) was the most agreed value amongst authors for establishing the fuel cell unit direct manufacturing cost, although another study established a fuel cell unit direct cost of 793 €/kW. [4], [5], [44]

Direct manufacturing costs of the FCET power unit (2022-2023)			
Component	2022	2025	2030
Fuel cell unit (€/kW)	460	340	170
Power battery (€/kWh)	370	320	230

Table 18. Fuel cell unit and power battery direct manufacturing costs for years 2022, 2025 and 2030. [44]

Direct manufacturing costs of the FCET power unit			
Component	2022	2030	2040
Fuel cell unit (€/kW)	460	230	100
Power battery (€/kWh)	407	250	223

Table 19. Fuel cell unit and power battery manufacturing costs for years 2022, 2030 and 2040. [5]

Direct manufacturing costs of the FCET power unit			
Component	2023	2030	2040
Fuel cell stack (€/kW)	793	289	232
Power battery (€/kWh)	392	232	186

Table 20. Fuel cell unit and power battery manufacturing costs for years 2023, 2030 and 2040. [4]

Considering 460 €/kW for period 2022-2023 is seen as optimistic bearing in mind the range of prices for the fuel cell stack previously mentioned. Therefore, the value selected as the direct manufacturing cost of the fuel cell unit for the period 2022-2023 in this report for further calculations will be 793 €/kW.

For 2030, the direct cost of the fuel cell stack varies depending on the author as these values are estimates done assuming lower costs due to the improvement of technologies and economies of scale among other factors (see *Tables 18, 19* and *20*). In order to decide on a value for each of the studied years the highest value will be multiplied by 0.5, the lowest value will be multiplied by 0.2 and the middle value will be multiplied by 0.3 so that the selected number is not too optimistic. The established value for further calculations in this report will be 248 €/kW.

As for 2040 the same as in 2030 occurs: the direct manufacturing cost of the fuel cell stack is an estimation done by each author, varying depending on the assumptions made (see *Tables 18, 19* and 20). Therefore, the selected value will be obtained by multiplying by 0.7 the highest value and by 0.3 the lowest one. This results in a unitary cost of 192.4€/kW.

Table 21 shows a summary of the direct manufacturing costs of the fuel cell unit in €/kW for years 2023, 2030 and 2040 that will be used for further calculations in this report.

Summary of the direct manufacturing costs of the fuel cell unit (€/kW)			
Component	**2023**	**2030**	**2040**
Fuel cell unit (€/kW)	793	248	192,4

Table 21. Summary of the direct manufacturing costs of the fuel cell unit in kW for years 2023, 2030 and 2040. [4], [5], [44]

FCET power battery direct manufacturing costs

The power battery direct manufacturing costs along the years established by different studies are more similar than the fuel cell unit costs. This can be seen in *Tables 18, 19* and *20*.

In order to decide on a value for each of the studied years, the highest value will be multiplied by 0.5, the lowest value will be multiplied by 0.2 and the middle value will be multiplied by 0.3 so that the selected number is not too optimistic, and then the three of them will be added. In case there are only two data available, as in year 2040, the highest value will be multiplied by 0.7 and the lowest one by 0.3. Moreover, years 2022 and 2023 are considered to belong to the same period.

For 2023 the calculated direct manufacturing cost is 395 €/kWh, which decreases to 241€/kWh in 2030 and reaches 212 €/kWh in 2040. [4], [5], [44]

The following table summarizes the direct manufacturing costs of the FCET power unit for years 2023, 2030 and 2040:

Summary of the direct manufacturing costs of the FCET power unit			
Component	**2023**	**2030**	**2040**
Fuel cell unit (€/kW)	793	248	192,4
Power battery (€/kWh)	395	241	212

Table 22. Summary of the fuel cell unit and power battery direct manufacturing costs in €/kW and €/kWh for years 2023, 2030 and 2040. [4], [5], [44]

Considering a fuel cell power unit of 180 kW and a power battery size of 72 kWh, *Table 23* shows the total direct manufacturing costs of the FCET power unit in €:

Total direct manufacturing costs of the FCET power unit (€)			
Component	**2023**	**2030**	**2040**
Fuel cell unit	142.740,00	44.550,00	34.632,00
Power battery	28.447,20	17.323,20	15.256,80

Table 23. Total direct manufacturing costs for the fuel cell and power battery in € for years 2023, 2030 and 2040. [4], [5], [44]

FCET and BET power electronics direct manufacturing costs

Power electronics are a key part of FCETs' and BETs' technological infrastructure as they have the ability to efficiently control and convert electricity, meaning that they can convert DC (Direct Current) into AC (Alternating Current), which is the type of current required by the electric motor to work, and vice versa. [38]

Additionally, power electronics are also involved in the regenerative braking, as they convert the AC power produced by the motor (which in this case transforms into a generator) into DC through a rectifier in order to recharge the truck's electric battery. [38]

For truck's belonging to the 5-LH category, the specification for power electronics is 350kW. As it can be seen in *Tables 24* and *25*, the direct manufacturing costs of these truck's components are between €22.5 and €25 per kW and this number is not expected to change for the next two decades according to different authors. [5], [39], [44], [45]

Power electronics direct manufacturing costs (2022-2030)			
	Specifications (kW)	**Cost multiplies (€/kW)**	**Total cost (€)**
Power electronics	350	22,50	7.875,00

Table 24. Power electronics direct manufacturing costs for 2022-2030 period. [39], [44]

Direct manufacturing costs of power electronics (€/kW)			
	2022	**2030**	**2040**
Power electronics (€/kW)	25	25	25

Table 25. Direct manufacturing costs of power electronics for years 2022, 2030 and 2040 in €/kW. [5]

For future calculations in this report, considering the data from *Tables 24* and *25*, the selected direct manufacturing costs for power electronics will be 24 €/kW for years 2023, 2030 and 2040, which is a value slightly higher than the average (23.75 €/kW). *Table 26* shows the total direct manufacturing costs of power electronics for the next decades considering a specification of 350 kW.

Total direct manufacturing costs of power electronics (€)			
Component	**2023**	**2030**	**2040**
Power electronics	8.400,00		

Table 26. Total direct manufacturing costs for power electronics in € for 2023, 2030 and 2040. [5], [39], [44]

Fuel cell unit, FCET power battery and FCET and BET power electronics retail price

For calculating the CAPEX and the TCO retail prices of all truck's components are required. In order to do so, indirect costs, which include research and development investments, sales and distribution costs, warranty expenditures, overheads and profit markups need to be considered. [44]

Indirect cost multipliers for high complex technologies in FCETs			
Complexity level	**ICM**	**2022**	**2030 (long-term)**
High 1	Warranty costs	0,066	0,037
	Non-warranty costs	0,328	0,233
	Total	0,394	0,27
High 2	Warranty costs	0,079	0,056
	Non-warranty costs	0,451	0,312
	Total	0,53	0,368

Table 27. Indirect cost multipliers for high complex technologies in FCETs for 2022 - 2023 and 2030 onwards (long term) periods. [44]

Indirect cost multipliers for high complex technologies in BETs			
Complexity level	**ICM**	**2022**	**2030 (long-term)**
High 1	Warranty costs	0,073	0,037
	Non-warranty costs	0,352	0,233
	Total	0,425	0,27
High 2	Warranty costs	0,084	0,056
	Non-warranty costs	0,486	0,312
	Total	0,57	0,368

Table 28. Indirect cost multipliers for high complex technologies in BETs for 2022 - 2023 and 2030 onwards (long term) periods. [8]

Indirect costs can be classified into "High 1" and "High 2" depending on their complexity level as it can be observed in *Tables 27 and 28.* The battery pack and the base glider components (in which power electronics are included) are considered to have a High 1 complexity, whereas the fuel cell unit and hydrogen storage tank belong to the High 2 category. [8], [44]

Based on the information coming from *Table 28*, BET power electronics have an ICM of 1.425 for 2022-2023 and of 1.27 for 2030 onwards. FCET power electronics as well as the FCET power battery have an indirect total cost multiplier of 1.394 for 2022-2023 and of 1.27 for 2030 and the following decades (long-term). The fuel cell unit has an indirect total cost multiplier of 1.53 for 2022-2023 and 1.368 for 2030 onwards (*Table 27*). [8], [44]

Considering these indirect cost multipliers as well as the direct manufacturing costs of the fuel cell unit, the power battery and the power electronics previously calculated (*Tables 23* and *26*), the retail price of this components has been computed.

It is needed to notice that for the fuel cell and the power battery inflation has not been considered for 2030 and 2040 as it is not seen as a key factor when determining the price. What is believed to play a major role when it comes to the price of these components is their technological development. However, for power electronics in BETs and FCETs a 2.5 % annual inflation rate will be considered as its direct manufacturing costs do not vary throughout the following decades, which implies that this component has reached its maturity. [43]

The figures in *Tables 29* and *30* are the retail prices that will be used for calculating the CAPEX and the TCO in this report.

Retail price of the FCET power unit and FCET power electronics (€)			
Component	**2023**	**2030**	**2040**
Fuel cell unit	218.392,20	60.944,40	47.376,58
Power battery	39.655,40	22.000,46	19.376,14
Power electronics	11.709,60	12.680,90	16.232,62

Table 29. Retail price of the FCET power unit and FCET power electronics in € for years 2023, 2030 and 2040. [44]

Retail price of the BET power electronics (€)			
Component	**2023**	**2030**	**2040**
Power electronics	11.970,00	12.680,90	16.232,62

Table 30. Retail price of the BET power electronics in € for years 2023, 2030 and 2040. [8], [43]

3.1.2. ENERGY STORAGE

3.1.2.1. DIESEL, E-DIESEL AND HVO FUEL TANK

The diesel fuel tank in 2010 had a manufacturing cost range that was between €1.4 and €2.5 per litre, being 2.0 €/l the average value. Considering a Spanish inflation rate of 27.96 % from 2010 to 2023, *Table 31* shows the 2023 diesel fuel tank manufacturing cost in 2023. [46], [47]

The diesel fuel tank is the same engine as the one used in e-diesel and HVO trucks and therefore the three of them have the same direct manufacturing cost. [4], [5], [31], [32], [44]

Diesel fuel tank direct manufacturing cost (€/l)			
	Low	**High**	**Most likely**
Diesel/e-diesel/HVO tank	1,79	3,20	2,56

Table 31. Diesel, e-diesel and HVO fuel tank direct manufacturing cost in €/l for year 2023. [46], [47]

For ICE trucks belonging to the 5-LH category, the quantity of fuel carried on their deposit varies, being 1,510 litres the maximum allowed by the Spanish legislation for 4x2 axel trucks. Diesel fuel tanks have an average capacity of 500 litres and HDVs can carry one or two fuel deposits. [48], [49]

In this report, for further calculations, it will be considered that diesel, e-diesel and HVO trucks from the 5-LH VECTO group carry one or two fuel tanks whose total capacity is 700 litres for a 500 km daily driving range, 1,000 litres for an 800 km driving range and 1,200 litres for a 1,000 km daily driving range truck. The total diesel fuel tank manufacturing cost is showed in *Table 32*. [48], [49]

Total diesel's fuel tank manufacturing cost (€)			
	Low	High	Most likely
5-LH (500 km)	1.254,01	2.239,30	1.791,44
5-LH (800 km)	1.791,44	3.199,00	2.559,20
5-LH (1000 km)	2.149,73	3.838,80	3.071,04

Table 32. Total direct manufacturing cost for diesel, e-diesel and HVO fuel tank in € for year 2023. [46], [47], [48], [49]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, an annual inflation rate of 2.5% will be assumed for estimating the diesel, e-diesel and HVO fuel tank total direct manufacturing cost for years 2030 and 2040 (*Table 33*). [43]

Diesel tank direct manufacturing cost (€)						
	Low		High		Most likely	
	2030	2040	2030	2040	2030	2040
5-LH (500 km)	1.490,62	1.908,12	2.661,82	3.407,36	2.129,46	2.725,89
5-LH (800 km)	2.129,46	2.725,89	3.802,61	4.867,66	3.042,08	3.894,13
5-LH (1000 km)	2.555,35	3.271,07	4.563,13	5.841,19	3.650,50	4.672,95

Table 33. Total direct manufacturing cost for diesel, e-diesel and HVO fuel tank in € for 2030 and 2040. [43], [46], [47], [48], [49]

For estimating the CAPEX and the TCO in this report, the input needed is the retail price for the studied years. Therefore, the most likely values for diesel, e-diesel and HVO fuel tank direct manufacturing costs will be selected and multiplied by 1.36, which is the estimated indirect cost multiplier [5], [6], [45]. The following tables shows a summary of these figures *(Table 34)*:

Diesel tank most likely retail price (€)			
	Most likely		
	2023	2030	2040
5-LH (500 km)	2.436,36	2.896,06	3.707,21
5-LH (800 km)	3.480,51	4.137,24	5.296,01
5-LH (1000 km)	4.176,61	4.964,68	6.355,21

Table 34. Diesel, e-diesel and HVO most likely retail price in € for years 2023, 2030 and 2040. [5], [6], [43], [45], [46], [47], [48], [49]

3.1.2.2. CNG STORAGE TANK

The CNG storage tank varies in size depending on the trucks driving range. For 5-LH trucks with a 500 km daily driving range the tank size changes from 139 kg in 2023 to 109 kg for the following decades, for trucks with an 800 km daily driving range it varies from 180 kg in 2023 to 174 kg for 2030 and 2040 and for a 1,000 km daily driving range the tank size remains constant throughout the years (180 kg). *Table 35* summarizes the different sizes of the CNG tanks. [4]

CNG tank size (kg)			
	2023	2030	2040
5-LH (500 km)	139	109	109
5-LH (800 km)	180	174	174
5-LH (1000 km)	180	180	180

Table 35. CNG tank sizes in kg based on the truck's daily driving range for 2023, 2030 and 2040. [4]

The direct manufacturing cost of the CNG tank in €/kg for years 2023, 2030 and 2040 can be seen in *Table 36*. [4]

CNG tank direct manufacturing cost (€/kg)			
Component	2023	2030	2040
CNG tank (€/kg)	82	68	62

Table 36. CNG tank direct manufacturing cost in €/kg for years 2023, 2030 and 2040. [4]

Considering the CNG different tank sizes in *Table 35* and the direct manufacturing cost in €/kg in *Table 36*, the total manufacturing cost of the CNG tanks for years 2023, 2030 and 2040 is obtained (*Table 37*).

Total CNG tank direct manufacturing cost (€)			
	2023	2030	2040
5-LH (500 km)	11.398,00	7.412,00	6.758,00
5-LH (800 km)	14.760,00	11.832,00	10.788,00
5-LH (1000 km)	14.760,00	12.240,00	11.160,00

Table 37. Total direct manufacturing cost of CNG tanks in € based on daily driving ranges for years 2023, 2030 and 2040. [4]

For estimating the CAPEX and the TCO, the retail price of the CNG tank is required for the studied years as one of the inputs. Therefore, the total direct manufacturing cost from *Table 37* will be multiplied by 1.36, which is the estimated indirect cost multiplier [5], [6], [45].

Additionally, an annual inflation rate of 2.5 % will be applied for calculating the CNG tank retail price for 2030 and 2040 as this component is considered to be mature enough so that its technological development is less relevant than inflation when establishing its price in the future [43]. The following tables shows a summary of these figures (*Table 38*):

Total CNG tank retail price (€)			
	2023	2030	2040
5-LH (500 km)	15.501,28	11.982,33	13.985,01
5-LH (800 km)	20.073,60	19.127,76	22.324,70
5-LH (1000 km)	20.073,60	19.787,34	23.094,51

Table 38. CNG tank retail price in € based on daily driving range for years 2023, 2030 and 2040 selected for this report. [4], [5], [6], [43], [45]

3.1.2.3. HYDROGEN STORAGE TANK

The hydrogen tank size in 5-LH fuel-cell trucks varies depending on the daily driving range and the year as it is expected that the hydrogen consumption lowers in the close future due to technological improvements, resulting in smaller tank sizes. [39]

This report considers compressed hydrogen gas at 700 bar, as it has a higher volumetric density (27 g H_2/l) in comparison to 350 bar hydrogen trucks (16 g H_2/l), which allows higher driving ranges. [39]

The current and the expected hydrogen tank sizes estimated changes depending on the author, although all of them agree on the same order of magnitude. *Tables 39* and *40* shows different tank sizes selected for computing the CAPEX and the TCO in other reports. *Table 41* shows the hydrogen capacity that the tank should have so that the daily driving range can be covered without refuelling.

Hydrogen tank size (kg)			
	2022	2030	2040
5-LH (500 km)	40	28	27
5-LH (800 km)	63	45	42
5-LH (1000 km)	79	56	53

Table 39. Hydrogen tank size in kg based on the daily driving range for years 2022, 2030 and 2040. [5]

FCET tank size (kg)			
	2023	2030	2040
5-LH (500 km)	45	33	32
5-LH (800 km)	73	54	51
5-LH (1000 km)	80	67	64

Table 40. FCET tank size in kg depending on the daily driving range for years 2023, 2030 and 2040. [4]

Hydrogen tank capacity required for covering the driving range without refuelling (kg)		
	2022	**2030**
5-LH (500 km)	45	33
5-LH (800 km)	73	54
5-LH (1000 km)	92	68

Table 41. Hydrogen tank capacity in kg required for covering the daily driving range without refuelling for years 2022 and 2030. [39]

In order to establish the tank size for further calculations in this report the most repeated values in *Tables 39*, *40* and *41* will be selected. In case there is a different value for each table, the weighted average will be done giving more importance to the highest value. The result will be rounded to the upper units.

For 2022-2023 period and for year 2030 the highest value will be multiplied by 0.5, the lowest value will be multiplied by 0.2 and the middle value will be multiplied by 0.3. For 2040 there are only two data available. Therefore, the highest value will be multiplied by 0.7 and the lowest value by 0.3.

For years 2022-2023 the hydrogen tank size established for 5-LH trucks with a 500 km daily driving range is 45 kg, for 800 km daily driving range trucks it is 73 kg and for trucks with 1,000 km daily driving range the tank size selected is 84 kg. [4], [5], [39]

For 2030, the tank size selected for a daily driving range of 500 km is 33 kg, for an 800 km daily driving range it is 54 kg and for trucks with a daily driving range of 1,000 km it is 64 kg. [4], [5], [39]

For 2040, the established tank sizes based on the daily driving ranges will be the average numbers between *Tables 39* and *40*: 30 kg (500 km daily driving range), 47 kg (800 km daily driving range) and 59 kg (1,000 daily driving range). [4], [5]

Table 42 summarizes the tank sizes selected for further calculations in this report based on the driving range for years 2023, 2030 and 2040.

Selected hydrogen tank size (kg)			
	2023	**2030**	**2040**
5-LH (500 km)	45	33	31
5-LH (800 km)	73	54	49
5-LH (1000 km)	86	66	61

Table 42. Selected hydrogen tank size for this report in kg for years 2023, 2030 and 2040 based on the different daily driving ranges. [4], [5], [39]

The hydrogen tank direct manufacturing cost vary depending on its size. *Tables 43* and *44* shows different estimations of the direct manufacturing costs for this component depending on the author for years 2023, 2030 and 2040. [4], [44]

Hydrogen tank direct manufacturing cost (€/kg)			
Component	**2023**	**2030**	**2040**
Hydrogen tank (€/kg)	1.211	810	648

Table 43. Hydrogen tank direct manufacturing cost in €/kg for years 2023, 2030 and 2040. [4]

FCET tank direct manufacturing cost (€/kg)			
Component	**2022**	**2025**	**2030**
Hydrogen tank (€/kg)	900	660	525

Table 44. FCET tank direct manufacturing cost in €/kg for 2022, 2025 and 2030. [44]

The reviewed literature agrees on a magnitude order, yet it does not agree on a specific value for the hydrogen tank direct manufacturing costs. Hence the established values for futures calculations in this report will be the weighted average of the figures proposed by the different authors. [4], [44]

Table 45 shows the established direct manufacturing costs for this report (70% weight from *Table 43* and 30% weight from *Table 44* as costs on *Table 44* are considered to be optimistic when it comes to the development of economies of scale in the close future for this component).

Hydrogen tank direct manufacturing cost (€/kg)			
Component	**2023**	**2030**	**2040**
Hydrogen tank (€/kg)	1.117,7	724,5	648

Table 45. Hydrogen tank direct manufacturing cost in €/kg for years 2023, 2030 and 2040 established for this report. [4], [44]

By multiplying the selected tank sizes by the unitary direct manufacturing cost established the total manufacturing cost is obtained as it can be observed in *Table 46*.

Hydrogen tank total direct manufacturing costs (€)			
	2023	**2030**	**2040**
5-LH (500 km)	50.296,50	23.908,50	20.088,00
5-LH (800 km)	81.592,10	39.123,00	31.752,00
5-LH (1000 km)	96.122,20	47.817,00	39.528,00

Table 46. Hydrogen tank total direct manufacturing cost in € for years 2023, 2030 and 2040 based on the daily driving ranges. [4], [5], [39], [44]

Indirect costs can be classified into "High 1" and "High 2" depending on their complexity level. The hydrogen storage tank belongs to the High 2 category. The indirect cost multiplier that will be used for obtaining the retail price depending on the year is showed in *Table 47*. [44]

Indirect cost multipliers for high complex FCET technologies			
Complexity level	ICM	2022	2030 (long-term)
High 2	Warranty costs	0,079	0,056
	Non-warranty costs	0,451	0,312
	Total	0,53	0,368

Table 47. Indirect cost multiplier for "High 2" complex FCET technologies for 2022-2023 and the long term (2030 onwards). [44]

For the hydrogen tank, inflation will not be considered for 2030 and 2040 as it is not seen as a key factor when determining the price. What is believed to play a major role when it comes to the price of this component is its technological development as the hydrogen tank technology is not considered mature yet.

For computing the CAPEX and the TCO the retail price of components is required. *Table 48* summarises the hydrogen tank retail price based on the driving range for years 2023, 2030 and 2040.

Hydrogen tank retail price (€)			
	2023	2030	2040
5-LH (500 km)	76.953,65	32.706,83	27.480,38
5-LH (800 km)	124.835,91	53.520,26	43.436,74
5-LH (1000 km)	147.066,97	65.413,66	54.074,30

Table 48. Hydrogen tank retail price in € for years 2023, 2030 and 2040 based on daily driving ranges. [4], [5], [39], [44]

3.1.2.3. BET ENERGY BATTERY

The battery capacity of BETs depends on the daily driving range and the selected year, as improvements are expected when it comes to the truck's aerodynamics, rolling resistant coefficients and the chassis weight in addition to the improvement of the transmission's efficiency. [5], [35]

Tables 49 and *50* shows different battery sizes in kWh depending on the truck's daily driving range and the year in order to compute the CAPEX and the TCO. It can be observed that although every author has selected different values they agree on the order of magnitude. [4], [5], [35]

BET Battery size (kWh)			
	2022	2030	2040
5-LH (500 km)	800	590	590
5-LH (800 km)	1300	940	940
5-LH (1000 km)	1650	1190	1190

Table 49. BET battery size based on the daily driving range in kWh for years 2022, 2030 and 2040. [5], [35]

BET battery size (kWh)			
	2023	2030	2040
5-LH (500 km)	760	405	405
5-LH (800 km)	1000	680	680
5-LH (1000 km)	1000	870	870

Table 50. BET battery size based on the daily driving range in kWh for years 2023, 2030 and 2040. [4]

For further calculations in this report the battery size used will be the weighted average values obtained from *Tables 49* and *50* rounded to units. The highest value will be multiplied by 0.7 and the lowest one by 0.3.

For the 2022-2023 period, the selected battery sizes are 788 kWh for daily driving ranges of 500 km, 1210 kWh for BETs with an 800 km daily driving range and 1455 kWh for driving ranges of 1,000 km.

For 2030 and 2040, the assumptions made when it comes to future technological improvements have led to selecting the same values for computing the weighted average. For 5-LH trucks with a 500 km daily driving range the selected battery size is 535 kWh, for trucks with an 800 km daily driving range 862 kWh is the established value and when it comes to a 1,000 km daily driving range the selected battery size is 1094 kWh.

Table 51 summarizes the established battery sizes in kWh for further calculations on this report for years 2023, 2030 and 2040.

Established BET battery size (kWh)			
	2023	2030	2040
5-LH (500 km)	788	535	535
5-LH (800 km)	1210	862	862
5-LH (1000 km)	1455	1094	1094

Table 51. Established BET battery sizes in kWh based in the daily driving range for years 2023, 2030 and 2040. [4], [5], [35]

The unitary direct manufacturing cost of the energy battery from the 5-LH BETs in €/kWh can be observed in *Table 52* for years 2023, 2030 and 2040. [4]

BET's battery direct manufacturing cost (€/kWh)			
Component	2023	2030	2040
Energy battery (€/kWh)	221	118	95

Table 52. Direct manufacturing cost of the BETs energy battery in €/kWh for years 2023, 2030 and 2040. [4]

Other publications established a battery cost of between €147 and €180 per kWh for 2023, of 80 €/kWh for 2030 and of 68 €/kWh for 2040. The selected cost will be the weighted average for avoiding being optimistic. For 2023 the highest value will be multiplied by 0.7, the lowest one by 0.2 and the middle value by 0.3. For 2030 and 2040 the highest value will be multiplied by 0.7 and the lowest one by 0.3 as there are only two data available. [4], [6], [8], [35]

Table 53 shows the selected value of the BET's battery direct manufacturing cost that will be used in this report for further calculations.

BET's battery direct manufacturing cost (€/kWh)			
Component	**2023**	**2030**	**2040**
Energy battery (€/kWh)	193,9	106,6	86,9

Table 53. Direct manufacturing costs of the BETs energy battery in €/kWh for years 2023, 2030 and 2040 established for this report. [4], [6], [8], [35]

Considering the different battery sizes based on the year and the driving range from *Table 51* as well as the unitary direct manufacturing cost of this component from *Table 53* the total direct manufacturing costs for years 2023, 2030 and 2040 are obtained (*Table 54*).

BET Battery total direct manufacturing cost (€)			
	2023	**2030**	**2040**
5-LH (500 km)	152.793,20	57.031,00	46.491,50
5-LH (800 km)	234.619,00	91.889,20	74.907,80
5-LH (1000 km)	282.124,50	116.620,40	95.068,60

Table 54. BET's battery total direct manufacturing cost in € for years 2023, 2030 and 2040 based on the daily driving range. [4], [5], [6], [8], [35]

For calculating the CAPEX and the TCO the input required is the retail price, not the direct manufacturing costs. Hence the total direct manufacturing costs previously calculated (*Table 54*) will be multiplied by an indirect cost multiplier which considers research and development investments, sales and distribution cost, warranty expenditures, overheads and profit markups. [8]

Indirect cost multipliers for high complex technologies in BETs			
Complexity level	**ICM**	**2022**	**2030 (long-term)**
High 2	Warranty costs	0,084	0,056
	Non-warranty costs	0,486	0,312
	Total	0,57	0,368

Table 55. Indirect cost multipliers for "High 2" complex technologies in BETs for 2022-2023 and 2030 onwards (long term). [8]

The energy battery from BET's is considered to have a High 2 complexity, so for the 2022-2023 period the indirect cost multiplier will be 1.57 and for 2030 onwards it will be 1.368 (*Table 55*). [8]

For the BETs battery inflation will not be considered for 2030 and 2040 as it is not seen as a key factor when determining the price. What is believed to play a major role when it comes to the price of this component is its technological development as the energy battery technology is not considered mature yet.

The energy battery retail prices for BETs in € for years 2023, 2030 and 2040 selected as one of the inputs for computing the CAPEX and the TCO are summarized in *Table 56*.

BET Battery retail price (€)			
	2023	2030	2040
5-LH (500 km)	239.885,32	78.018,41	63.600,37
5-LH (800 km)	368.351,83	125.704,43	102.473,87
5-LH (1000 km)	442.935,47	159.536,71	130.053,84

Table 56. BET's energy battery retail price in € based on daily driving ranges for years 2023, 2030 and 2040. [4], [5], [6], [8], [35]

3.1.3. REST OF THE TRUCK

When it comes to the "Rest of the truck" components it is necessary to classify them according to the different technologies. Hence this section will be divided into three subsections: FCET auxiliar components, BET auxiliar components and CNG, diesel, e-diesel and HVO auxiliar components. When it comes to the chassis, the same direct manufacturing cost will be assumed for all technologies, yet the indirect cost multipliers will vary based on the type of truck.

3.1.3.1. FCET AUXILIAR COMPONENTS

The main FCET auxiliar components (air compressor, steering pump, PTC heater, air conditioning, thermal management and onboard FCET charger as well as the chassis) in \$2022/kW are showed below in *Table 57*. For each component a range of direct manufacturing costs is given and it is divided into low, medium and high. [45]

Auxiliar FCET component's direct manufacturing costs (\$2022/kW)			
Auxiliar component	Low	Medium	High
Air compressor	1.187	1.648	2.088
Steering pump	220	330	428
PTC heater	49	82	126
Air conditioning	52	77	137
Thermal management	9	10	12
Onboard charger	44	74	110

Table 57. Auxiliar FCET component's direct manufacturing costs in \$2022/kW. [45]

As this report focuses on studying the CAPEX and TCO for 2023 among other years in euros, *Table 58* shows the equivalent of *Table 57* in €2023. In order to do so, first the average exchange rate in 2022 between euros and US dollars has been found (1.0538 \$2022 equals 1 €2022). Then, in order to transform €2022 into €2023 the inflation rate has been taken into account (1 €2022 equals 1.035 €2023). [50], [51]

Auxiliar FCET component's direct manufacturing costs (€2023/kW)			
Auxiliar component	**Low**	**Medium**	**High**
Air compressor	1.165,82	1.618,60	2.050,75
Steering pump	216,08	324,11	420,36
PTC heater	48,13	80,54	123,75
Air conditioning	51,07	75,63	134,56
Thermal management	8,84	9,82	11,79
Onboard charger	43,22	72,68	108,04

Table 58. Auxiliar FCET component's direct manufacturing costs in €2023/kW. [45], [50], [51]

Another author has selected different direct manufacturing costs for the FCETs' main auxiliar components which can be observed in *Table 59*. [44]

FCET base glider direct manufacturing costs (2022-2030)	
Component	**Cost direct multiplier (€/kW)**
Air compressor	1.250,00
Steering pump	240,00
Air conditioning	58,00
Heater	63,00
Thermal management	7,50

Table 59. FCET base glider direct manufacturing costs for period 2022-2030 in €/kW. [44]

In order to establish the unitary direct manufacturing costs for year 2023 of the different auxiliar components for further calculations in this report the average between the low, medium and high columns form *Table 58* and the cost direct multiplier from *Table 59* will be computed (*Table 60*).

FCET main auxiliar components' direct manufacturing costs (€/kW)	
Component	**FCET**
Air compressor	1.521,29
Steering pump	300,14
Air conditioning	79,82
Heater	78,86
Thermal management	9,49
Onboard charger	74,65

Table 60. FCET main auxiliar components' unitary direct manufacturing costs in €/kW selected for year 2023. [44], [45]

For computing the total direct costs of the FCET main auxiliar components it is necessary to know the specifications of these items. *Tables 61* and *62* show different specifications considered by various authors.

Auxiliar FCET components' specifications (kW)	
Auxiliar component	**FCET**
Air compressor	3
Steering pump	5
PTC heater	10
Air conditioning	10
Thermal management	350
Onboard charger	11

Table 61. Main auxiliar FCET components' specifications in kW. [45]

FCET auxiliar components' specifications (kW)	
Component	**FCET**
Air compressor	6
Steering pump	9
Air conditioning	10
Heater	10
Thermal management	350
Onboard charger	6,6

Table 62. FCET main auxiliar components' specifications in kW. [39], [44]

As it can be observed in *Tables 61* and *62* authors agree on the order of magnitude of the auxiliar components' specifications, yet not on the exact values. Hence, the average between *Tables 61* and *62* will be established as the specifications for further calculations in this report (*Table 63*).

Auxiliar FCET components' specifications (kW)	
Auxiliar component	**FCET**
Air compressor	4,5
Steering pump	7
PTC heater	10
Air conditioning	10
Thermal management	350
Onboard charger	8,8

Table 63. FCET main auxiliar components' specifications in kW selected for this report. [39], [44], [45]

The total direct manufacturing costs of the main auxiliar components for FCETs are obtained by multiplying the unitary direct manufacturing costs (€/kW) from *Table 60* by these components' specifications from *Table 63*. Additionally, the chassis also needs to be considered as one of the base glider components. According to the reviewed literature its total direct manufacturing costs in 2023 is of 25,375.00 €. [8], [39], [44] The total direct manufacturing costs for 2023 are summarized in *Table 64*:

FCET base glider total direct manufacturing costs (€)	
Component	**2023**
Chassis	25.375,00
Air compressor	6.845,82
Steering pump	2.100,96
Air conditioning	798,15
Heater	788,55
Thermal management	3.320,63
Onboard charger	656,89

Table 64. FCET's main auxiliar components total direct manufacturing costs in € for year 2023. [8], [39], [44], [45], [50], [51]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, which is higher than this target, an annual inflation rate of 2.5% will be used for calculating the total direct manufacturing costs of the FCET main auxiliar components for 2030 and 2040 (*Table 65*). [43]

FCET base glider total direct manufacturing costs (€)			
Component	**2023**	**2030**	**2040**
Chassis	25.375,00	30.162,90	38.611,06
Air compressor	6.845,82	8.137,52	10.416,72
Steering pump	2.100,96	2.497,38	3.196,86
Air conditioning	798,15	948,75	1.214,48
Heater	788,55	937,34	1.199,87
Thermal management	3.320,63	3.947,18	5.052,72
Onboard charger	656,89	780,84	999,54

Table 65. FCET's main auxiliar components total direct manufacturing costs in € for years 2023, 2030 and 2040. [8], [39], [43], [44], [45], [50], [51]

For calculating the CAPEX and the TCO the input required are the retail prices. In order to compute them the total direct manufacturing costs need to be multiplied by the corresponding indirect cost multiplier. The FCET's main auxiliar components belong to the High 1 complexity level. Hence *Table 66* will be the ICMs applied in this case.

Indirect cost multipliers for high complex technologies in FCETs			
Complexity level	**ICM**	**2022**	**2030 (long-term)**
High 1	Warranty costs	0,066	0,037
	Non-warranty costs	0,328	0,233
	Total	0,394	0,27

Table 66. Indirect costs multipliers of "High 1" technologies for the main FCET's auxiliar components for the 2022-2023 period and 2030 onwards. [44]

Table 66 summarizes the retail prices of the main FCET's auxiliar components in € for years 2023, 2030 and 2040 that will be used in this report for calculating the CAPEX and the TCO.

FCET base glider total direct manufacturing costs (€)			
Component	**2023**	**2030**	**2040**
Chassis	35.372,75	38.306,88	49.036,05
Air compressor	9.543,07	10.334,66	13.229,23
Steering pump	2.928,74	3.171,68	4.060,02
Air conditioning	1.112,62	1.204,91	1.542,39
Heater	1.099,24	1.190,42	1.523,84
Thermal management	4.628,95	5.012,92	6.416,96
Onboard charger	915,71	991,66	1.269,41

Table 67. Retail price of the main FCET's auxiliar components in € for years 2023, 2030 and 2040. [8], [39], [43], [44], [45], [50], [51]

Other sources estimates that the total "rest of the truck" CAPEX component is around €80,000 for 2023. Adding all the components from *Table 67* the "rest of the truck" value obtained is of €55,601.08 for 2023. This indicates that there are other components that have not been considered in the previous analysis. Therefore, a fixed value of €25,000 will be added as "other components" for years 2023, 2030 and 2040. It will not be affected by inflation as among this components there might be some of them for which inflation is not a key factor when establishing their future prices. [4], [6]

Adding all the auxiliar components' retail prices for 2023, 2030 and 2040 the total "rest of the truck" values that will be introduced for computing the CPEX and the TCO are the following (*Table 68*):

FCET total "rest of the truck" retail price (€)			
	2023	**2030**	**2040**
Rest of the truck	80.601,08	85.213,13	102.077,90

Table 68. FCET total "rest of the truck" retail price in € for years 2023, 2030 and 2040. [4], [8], [39], [43], [44], [45], [50], [51]

3.1.3.2. BET AUXILIAR COMPONENTS

The main BET auxiliar components (air compressor, steering pump, PTC heater, air conditioning, thermal management and onboard BET charger as well as the chassis) in \$2022/kW are showed below in *Table 69*. For each component a range of direct manufacturing costs is given and it is divided into low, medium and high. [45]

BET main auxiliar components' direct manufacturing costs ($2022/kW)			
Auxiliar electric component	**Low**	**Medium**	**High**
Air compressor	1.187	1.648	2.088
Steering pump	220	330	428
PTC heater	49	82	126
Air conditioning unit	52	77	137
Thermal management	19	23	30
Onboard charger	49	79	165

Table 69. BET main auxiliar components' direct manufacturing costs in $2022/kW. [45]

For further calculations, it is required for the direct manufacturing costs to be in €2023. For achieving so, first it is needed to find the average exchange rate in 2022 between US dollars and euros (1 €2022 equals 1.0538 $2022). Then it is required to consider the Spanish inflation rate between 2022 and 2023, which is 3.5 %. *Table 70* shows the direct manufacturing costs of the main BET auxiliar components in €2023/kW. [50], [51].

BET main auxiliar components' direct manufacturing costs (€2023/kW)			
Auxiliar electric Component	**Low**	**Medium**	**High**
Air compressor	1.165,82	1.618,60	2.050,75
Steering pump	216,08	324,11	420,36
PTC heater	48,13	80,54	123,75
Air conditioning	51,07	75,63	134,56
Thermal management	18,66	22,59	29,46
Onboard charger	48,13	77,59	162,06

Table 70. Direct manufacturing costs of the main BET auxiliar components in €2023/kW. [45], [50], [51]

Table 71 shows the established direct manufacturing costs for the main BET auxiliar components by other authors on another report. As it can be observed in *Tables 70* and *71* the order of magnitude matches among different authors. [8]

BET base glider direct manufacturing costs (2022-2030)	
Component	**Cost direct multiplier (€/kW)**
Air compressor	1.250,00
Steering pump	240,00
Air conditioning	58,00
Heater	63,00
Thermal management	18

Table 71. BET base glider direct manufacturing costs for period 2022-2030 in €/kW. [8]

For establishing the unitary direct manufacturing costs of the main BET auxiliar components for year 2023, which will be required for further calculations in this report, the average between the low, medium and high columns from *Table 70* and the cost direct multiplier from *Table 71* will be computed. (*Table 72*).

BET main auxiliar components' direct manufacturing costs (€/kW)	
Auxiliar component	**BET**
Air compressor	1.521,29
Steering pump	300,14
PTC heater	78,86
Air conditioning	79,82
Thermal management	22,18
Onboard charger	95,93

Table 72. Unitary direct manufacturing costs of the main BET auxiliar components in €/kW selected for year 2023. [8], [45], [50], [51]

To compute the total direct manufacturing costs of the BET main auxiliar components the specifications for these items are required. *Tables 73* and *74* show different specifications considered in several reports.

Auxiliar BET components' specifications (kW)	
Auxiliar component	**BET**
Air compressor	3
Steering pump	5
PTC heater	10
Air conditioning	10
Thermal management	350
Onboard charger	11

Table 73. Main auxiliar BET components' specifications in kW. [33]

BET base glider components' specifications (kW)	
Auxiliar component	**BET**
Air compressor	6
Steering pump	9
PTC heater	10
Air conditioning	10
Onboard charger	44

Table 74. BET base glider components' specifications in kW. [8], [39]

The order of magnitude when it comes to the different auxiliar components' specifications is agreed among different authors as it can be observed on *Tables 73* and *74*, yet not the exact values. For further calculations on this report the average between *Tables 73* and *74* will be established as the auxiliar components' specifications (*Table 75*).

Auxiliar BET components' specifications (kW)	
Auxiliar component	**BET**
Air compressor	4,5
Steering pump	7
PTC heater	10
Air conditioning	10
Thermal management	350
Onboard charger	27,5

Table 75. BET main auxiliar components' specifications in kW selected for this report. [8], [39], [45]

For obtaining the total direct manufacturing costs of the main auxiliar components for the BETs, the unitary direct manufacturing costs (€/kW) from *Table 72* will be multiplied by these components' specifications from *Table 75*. Moreover, the chassis also needs to be considered as one of the base glider components. Its total direct manufacturing costs according to the reviewed literature escalated up to €25,375.00 in 2023. [8], [39], [44]

The total direct manufacturing costs for 2023 are summarized on *Table 76*:

BET base glider total direct manufacturing costs (€)	
Component	**2023**
Chassis	25.375,00
Air compressor	6.845,82
Steering pump	2.100,96
Air conditioning	798,15
Heater	788,55
Thermal management	7.762,13
Onboard charger	2.637,98

Table 76. BET's main auxiliar components total direct manufacturing costs in € for year 2023. [8], [39], [45], [50], [51]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, which are higher than this target, an annual inflation rate of 2.5% will be used for calculating the total direct manufacturing costs of the BET main auxiliar components for 2030 and 2040 (*Table 77*). [43]

BET base glider total direct manufacturing costs (€)			
Component	**2023**	**2030**	**2040**
Chassis	25.375,00	30.162,90	38.611,06
Air compressor	6.845,82	8.137,52	10.416,72
Steering pump	2.100,96	2.497,38	3.196,86
Air conditioning	798,15	948,75	1.214,48
Heater	788,55	937,34	1.199,87
Thermal management	7.762,13	9.226,73	11.810,99
Onboard charger	2.637,98	3.135,73	4.014,00

Table 77. BET's main auxiliar components total direct manufacturing costs in € for years 2023, 2030 and 2040. [8], [39], [43], [45], [50], [51]

For calculating the CAPEX and the TCO the input required are the retail prices. In order to compute them the total direct manufacturing costs need to be multiplied by the corresponding indirect cost multiplier. The BET's main auxiliar components belong to the High 1 complexity level. Hence *Table 78* will be the ICMs applied in this case.

Indirect cost multipliers for high complex technologies in BETs			
Complexity level	**ICM**	**2022**	**2030 (long-term)**
High 1	Warranty costs	0,073	0,037
	Non-warranty costs	0,352	0,233
	Total	0,425	0,27

Table 78. Indirect costs multipliers for "High 1" technologies for the main BET's auxiliar components for the 2022-2023 period and 2030 onwards (long term). [8]

Table 79 summarizes the retail prices of the main BET's auxiliar components in € for years 2023, 2030 and 2040 that will be used in this report for calculating the CAPEX and the TCO.

BET main auxiliar components' retail price (€)			
Component	**2023**	**2030**	**2040**
Chassis	36.159,38	38.306,88	49.036,05
Air compressor	9.755,29	10.334,66	13.229,23
Steering pump	2.993,87	3.171,68	4.060,02
Air conditioning	1.137,36	1.204,91	1.542,39
Heater	1.123,68	1.190,42	1.523,84
Thermal management	11.061,03	11.717,94	14.999,96
Onboard charger	3.759,13	3.982,38	5.097,78

Table 79. Main BET auxiliar components' retail price in € for years 2023, 2030 and 2040. [8], [39], [43], [45], [50], [51]

Other sources estimates that the total "rest of the truck" CAPEX component is around €80,000 for 2023. Adding all the components from *Table 79* the Rest of the truck value obtained is of €65,989.74 for 2023. This indicates that there are other components that have not been considered in the previous analysis. Therefore, a fixed value of €13,000 will be added as "other components" for years 2023, 2030 and 2040. It will not be affected by inflation as among this components there might be some of them for which inflation is not a key factor when establishing their future prices. [4], [6]

Adding all the auxiliar components' retail prices for 2023, 2030 and 2040 the total "rest of the truck" values that will be introduced for computing the CPEX and the TCO are the following (*Table 80*):

BET total "rest of the truck" retail price (€)			
	2023	2030	2040
Rest of the truck	78.989,74	82.908,87	102.489,27

Table 80. BET total "rest of the truck" retail price in € for years 2023, 2030 and 2040. [8], [39], [43], [45], [50], [51]

3.1.3.3. CNG, DIESEL, E-DIESEL AND HVO AUXILIAR COMPONENTS

The main auxiliar components considered for CNG, e-diesel, diesel and HVO technologies are the air compressor, the steering pump, the heater and the air conditioning unit as well as the chassis. *Table 81* shows in $2022/kW those components along with their unitary direct manufacturing costs. [45]

Main auxiliar components' direct manufacturing costs ($2022/kW)			
Auxiliar electric component	Low	Medium	High
Air compressor	1.187	1.648	2.088
Steering pump	220	330	428
PTC heater	49	82	126
Air conditioning	52	77	137

Table 81. Main auxiliar components' direct manufacturing costs for CNG, diesel, e-diesel and HVO technologies in $2022/kW. [45]

For further calculations the different direct manufacturing costs need to be expressed in €2023 (*Table 82*). For doing so, first it is required to apply the average exchange rate in 2022 between euros and US dollars (1.0538 $US equals 1 €2022). Then, it is needed to consider the Spanish inflation rate to transform €2022 into €2023 (1 €2022 equals 1.035 €2023). [50], [51]

BET main auxiliar components' direct manufacturing costs (€2023/kW)			
Auxiliar electric Component	Low	Medium	High
Air compressor	1.165,82	1.618,60	2.050,75
Steering pump	216,08	324,11	420,36
PTC heater	48,13	80,54	123,75
Air conditioning	51,07	75,63	134,56

Table 82. Main auxiliar components' direct manufacturing costs for CNG, diesel, e-diesel and HVO technologies in €2023/kW. [45], [50], [51]

Another author has selected different direct manufacturing costs for the main auxiliar components of CNG, diesel, e-diesel and HVO technologies that can be observed on *Table 83*. [8], [44]

Base glider direct manufacturing costs (2022-2030)	
Component	**Cost direct multiplier (€/kW)**
Air compressor	1.250,00
Steering pump	240,00
Air conditioning	58,00
Heater	63,00

Table 83. Base glider direct manufacturing costs for CNG, diesel, e-diesel and HVO technologies in €/kW for period 2022-2030. [8], [44]

For establishing the unitary direct manufacturing costs for year 2023 of the different auxiliar components for further calculations in this report the average between the low, medium and high columns from *Table 82* and the cost direct multiplier from *Table 83* will be computed (*Table 84*).

Main auxiliar components' direct manufacturing costs (€/kW)	
Component	**Cost direct multiplier (€/kW)**
Air compressor	1.521,29
Steering pump	300,14
Air conditioning	79,82
Heater	78,86

Table 84. Main auxiliar components' direct manufacturing costs for CNG, diesel, e-diesel and HVO technologies in €/kW selected for year 2023. [44], [45], [50], [51]

For computing the total direct manufacturing costs of these technologies' main auxiliar components it is necessary to know the specifications of these items. *Tables 85* and *86* show different specifications considered by various authors.

Main auxiliar components' specifications (kW)	
Auxiliar component	**CNG/diesel/e-diesel/HVO**
Air compressor	3
Steering pump	5
PTC heater	10
Air conditioning	10

Table 85. Main auxiliar CNG, diesel, e-diesel and HVO components' specifications in kW. [45]

Main auxiliar components' specifications (kW)	
Component	**CNG/diesel/e-diesel/HVO**
Air compressor	6
Steering pump	9
Air conditioning	10
Heater	10

Table 86. Main auxiliar CNG, diesel, e-diesel and HVO components' specifications in kW. [8], [39], [44]

As it can be observed in *Tables 85* and *86* authors agree on the order of magnitude of the auxiliar components' specifications, yet not on the exact values. Hence, the average between *Tables 85* and *66* will be established as the specifications for further calculations in this report (*Table 87*).

Main auxiliar components' specifications (kW)	
Auxiliar component	**CNG/diesel/e-diesel/HVO**
Air compressor	4,5
Steering pump	7
PTC heater	10
Air conditioning	10

Table 87. Main auxiliar components' specifications for CNH, diesel, e-diesel and HVO technologies in kW selected for this report. [8], [39], [44], [45]

In order to obtain the total direct manufacturing costs of the main auxiliar components for CNG, diesel, e-diesel and HVO trucks the unitary direct manufacturing costs (€/kW) from *Table 84* will be multiplied by these components' specifications from *Table 87*. In addition, the chassis also needs to be considered as one of the base glider components. Its total direct manufacturing costs according to the reviewed literature escalated up to €25,375.00 in 2023. [8], [39], [44]

The total direct manufacturing costs for 2023 are summarized in *Table 88*:

Auxiliar components' total direct manufacturing costs (€)	
Component	**2023**
Chassis	25.375,00
Air compressor	6.845,82
Steering pump	2.100,96
Air conditioning	798,15
Heater	788,55

Table 88. Main auxiliar components' total direct manufacturing costs in € for CNG, diesel, e-diesel and HVO trucks for year 2023. [8], [39], [44], [45], [50], [51]

The European Central Bank objective when it comes to the annual inflation rate is a 2% on the medium term. Considering the annual inflation rates from the previous five years in Spain, which is higher than this target, an annual inflation rate of 2.5% will be used for calculating the total direct manufacturing costs of the main auxiliar components of the mentioned technologies for 2030 and 2040 (*Table 89*). [43]

Main auxiliar components' total direct manufacturing costs (€)			
Component	**2023**	**2030**	**2040**
Chassis	25.375,00	30.162,90	38.611,06
Air compressor	6.845,82	8.137,52	10.416,72
Steering pump	2.100,96	2.497,38	3.196,86
Air conditioning	798,15	948,75	1.214,48
Heater	788,55	937,34	1.199,87

Table 89. Main auxiliar components' total direct manufacturing costs in € for CNG, diesel, e-diesel and HVO trucks for years 2023, 2030 and 2040. [8], [39], [43], [44], [45], [50], [51]

For computing the CAPEX and the TCO the retail price is the required input. When it comes to CNG, diesel, e-diesel and HVO technologies the ICM used for calculating the retail price will be 1.36, which is the selected ones based on the reviewed literature (*Table 90*). [5], [6], [45]

Main auxiliar components' retail price (€)			
Component	**2023**	**2030**	**2040**
Chassis	34.510,00	41.021,55	52.511,05
Air compressor	9.310,31	11.067,03	14.166,74
Steering pump	2.857,31	3.396,44	4.347,73
Air conditioning	1.085,48	1.290,30	1.651,69
Heater	1.072,43	1.274,78	1.631,83

Table 90. Main auxiliar components' retail price in € for CNG, diesel, e-diesel and HVO trucks for years 2023, 2030 and 2040. [5], [6], [8], [39], [43], [44], [45], [48], [50], [51]

Other sources estimates that the total "rest of the truck" CAPEX component is around €80,000 for 2023. Adding all the components from *Table 91* the rest of the truck value obtained is of €48,835.53 for 2023. This indicates that there are other components that have not been considered in the previous analysis. Therefore, a fixed value of €30,000 will be added as "other components" for years 2023, 2030 and 2040. It will not be affected by inflation as among this components there might be some of them for which inflation is not a key factor when establishing their future prices. [4], [6]

Adding all the auxiliar components' retail prices for 2023, 2030 and 2040 the total "rest of the truck" values that will be introduced for computing the CPEX and the TCO are the following (*Table 91*):

CNG, diesel, e-diesel and HVO total "rest of the truck" retail price (€)			
	2023	**2030**	**2040**
Rest of the truck	78.835,53	88.050,10	104.309,04

Table 91. CNG, diesel, e-diesel and HVO total "rest of the truck" retail price in € for years 2023, 2030 and 2040. [4], [5], [6], [8], [39], [43], [44], [45], [50], [51]

3.2. OPEX CALCULATION

The OPEX is subdivided into 4 different categories: tolls, fuel costs including the charging infrastructure, driver wages, insurance fees and operation and maintenance costs (O&M).

For computing the OPEX the following formula will be used:

$$OPEX = Tolls + Fuel\ costs\ (including\ charging\ infrastructure) + Driver\ wages + Insurance + O\&M$$

3.2.1. TOLLS

In Spain, as in other EU member states such as Germany, France or Italy, the implemented toll system is based on the travelled distance. In Spain, vehicles are charged €0.16 per travelled kilometre. This fee is the assumed average value, yet there are highways with no tolls and others with more expensive toll fees than the provided value. In the following table, which shows the toll cost per kilometre travelled, it can be observed that Spain is one of the EU countries with the cheapest distance-based road tolls. [4], [44]

Distance-based road tolls in the EU (€/km)	
Country	**Tolls (€/km)**
Hungary	0,475
Austria	0,44
Slovenia	0,38
France	0,32
Greece	0,26
Slovakia	0,248
Portugal	0,21
Italy	0,19
Belgium	0,184
Germany	0,183
Spain	0,16
Czechia	0,16
Netherlands	0,15
Poland	0,085
Bulgaria	0,036

Table 92. Cost per kilometre of the distance-based road tolls in the EU. [44], [4]

These tolls are located in highways. However, trucks also travel through urban areas in which there are no tolls. Based on the reviewed literature it can be established that inside the 5-LH category trucks with a daily driving range of up to 500 km travel 80% of the kilometres through highways, those with a daily driving range of up to 800 km cover 90%

of their kilometres through highways and those with the biggest daily driving range (1000 km) spend 95% of their kilometres on the highway *(Table 93).* [4]

Assumption on shares of VKT		
Class	**Highway**	**Local**
5-LH (500 km)	80%	20%
5-LH (800 km)	90%	10%
5-LH (1000 km)	95%	5%

Table 93. Summary of the shares of VKT (Vehicle Kilometres Travelled) for 5-LH trucks depending on their driving range. [4]

Bearing in mind the toll cost in Spain (€0.16/km) and the percentage of the total kilometres that the 5-LH trucks travel through highways depending on the driving range, the truck road tolls weighted depending on road type in Spain have been calculated in the following table:

Truck road tolls weighted based on road type (€/km)			
	5-LH (500 km)	**5-LH (800 km)**	**5-LH (1000 km)**
Spain	0,128	0,144	0,152

Table 94. Truck road tolls in Spain weighted based on road type. [4], [44]

Additionally, the European Parliament has also guaranteed that zero-emission trucks will receive a 50% discount when it comes to distance-based road tolls by 2023, which could increase to a 75% reduction. The motivation behind this discount is to make battery electric and fuel cell trucks more competitive in terms of TCO against diesel trucks as it is stated in the Eurovignette Directive. [4], [31], [44]

This discount has already been applied in EU-member states such as Germany, in which zero-emission trucks are exempted from road tolls. The following table *(Table 95)* shows the truck road tolls in Sapin weighted based on the road type taking into consideration whether the truck is zero-emission or not and applying the previously mentioned 50% discount when it corresponds. [4], [8], [31], [44]

Truck road tolls in Spain weighted based on road type (€/km)			
Technology	**5-LH (500 km)**	**5-LH (800 km)**	**5-LH (1000 km)**
Diesel/e-diesel/HVO/bio-CNG	0,128	0,144	0,152
BET/FCET	0,064	0,072	0,076

Table 95. Truck road tolls in Spain based on road type and taking into account the 50% discount established in the Eurovignette Directive for zero-emission trucks from 2023 onwards. [4], [31], [44]

In order to calculate the OPEX and the TCO, the toll costs per kilometres that will be used are the weighted ones based on the road type and with a 50% discount applied for zero-emission truck technologies as recorded in the Eurovignette Directive *(Table 95)*. This road toll costs will be considered constant for the 2023-2040 period. [4], [44] Considering the total travelled kilometres by truck during the first five years of usage based on its daily driving range and its powertrain technology the total costs of the road tolls per year are gathered in *Table 96*. [4], [31], [44]

Total cost of truck road tolls in Spain weighted based on road type (€)			
Technology	**5-LH (500 km)**	**5-LH (800 km)**	**5-LH (1000 km)**
Diesel/e-diesel/HVO/bio-CNG	15.265	22.802	30.620
BET/FCET	7.633	11.401	15.310

Table 96. Total truck's road toll cost per year in € based on its daily driving range, the road type and its technology. [4], [31], [44]

3.2.1.1. CO_2 ROAD FEES

It is also proposed in the Eurovignette Directive to charge heavy-duty vehicles such as 5-LH trucks with a CO_2 road fee for considering the external cost of CO_2 emissions which would be added to road tolls. According to this Directive, the charge would be defined based on the CO_2 emission class. [4], [44]

Based on the CO_2 classification HVO, e-diesel, bio-CNG and conventional power trains running on diesel belong to the CO_2 emission class 1, so the charge per kilometre would be €0.08/km. However, battery electric (BETs) and hydrogen-powered trucks (FCETs) are classified as zero-emission trucks and therefore are exempt from these charges. [4], [44]

The following table shows a summary of the CO_2 road charges in €/km based on the truck's powertrain technology:

Summary of CO_2 road charges (€/km)			
	5-LH (500 km)	**5-LH (800 km)**	**5-LH (1000 km)**
Diesel/HVO/bio-CNG/e-diesel	0,08	0,08	0,08
BET/FCET	0		

Table 97. CO_2 road charges in €/km depending on the truck's technology and daily driving range in €/km. [4], [44]

These CO_2 fees will be considered in this report when calculating the OPEX and the TCO as they are non-existent for zero-emission trucks in an attempt to make them more competitive in comparison to other powertrain technologies. This road charges will be considered constant for the 2023-2040 period.

Considering the total travelled kilometres by truck during its first five years of usage based on its daily driving range as well as its powertrain technology, the total CO_2 road charges per year are gathered in *Table 98*. [4], [44]

Summary of CO2 road charges (€)			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Diesel/HVO/bio-CNG/e-diesel	9.541	12.668	16.116
BET/FCET	0		

Table 98. Total CO_2 road charges in € based on the truck's daily driving range and its powertrain technology per year. [4], [44]

3.2.2. *FUEL COSTS INCLUDING CHARGING INFRASTRUCTURE*

The weighted average fuel and energy retail prices in the EU can be observed in *Table 99*. The weights have been assigned based on the shares of freight activity in each European country, expressed in tonnes.vehicke km (tkm, which is a unit of measure defined by the transport of one tonne of goods by a given transport service over one kilometre) for the different daily driving ranges. [52]

The diesel fuel retail price has been calculated by computing the average diesel retail prices in the EU between years 2020 and 2022, both included. [4]

The grid electricity, in which the charging costs are included, is the average for commercial non-household applications between years 2020 and 2022, both included. It has been assumed that 5-LH 500 km and 5-LH 800 km trucks charge their batteries 80% of the times at depots and 20% of the times at public charging stations. For 5-LH 1,000 km trucks it has been assumed that all the recharges occur at public charging stations. [4]

The green hydrogen retail price considered is the one coming from the lowest production pathway, which involves decentralized local production within the EU borders. The hydrogen refuelling infrastructure costs and all taxes related to the renewable energy production in the EU as well as the minimum level of taxes proposed in the Revision of the Energy Taxation Directive in Europe, which is €0.018/kg, are considered in order to obtain the retail price of at-the-pump hydrogen. [4]

The CO_2 source in e-diesel can have two different origins: concentrated point source (CPS) and direct air capture (DAC), which is more expensive and whose use is expected to grow in the following decades due to CPS limitations (100% CPS until 2030 and 100% DAC from 2040 onwards). The cheapest production pathway for e-diesel has been considered, which is importing e-diesel from Brazil to the EU. Apart from the import costs, the fuel distribution and handling costs in the EU have been considered (€0.15/litre) as well as the minimum level of fuel taxes and excise duties (€0.0057/litre) for estimating the e-diesel retail price. [4]

For HVO the estimated production cost for 2023 is of €1.01/litre and the handling and distribution costs have been assumed to be €0.15/litre. The HVO production technology is considered to have reached its full maturity, so its costs are expected to remain constant the following decades. The minimum level of fuel taxes and excise duties are assumed, which is €0.2/litre. This makes a total retail price of €1.36/litre. [4]

The estimated production cost of bio-CNG in the EU coming from waste and residue materials is around €2.03/kg, assuming no cost reduction in the future. Moreover, the refuelling infrastructure cost is estimated to be €0.64/kg and the minimum fuel taxes and excise duties escalates up to €0.007/kg. Adding all up the obtained retail price of the bio-CNG is of €2.68/kg. [4]

Table 99 summarizes the fuel and energy retail prices previously mentioned.

Weighted average fuel and energy retail prices in the EU			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Diesel (€/l)	1,22	1,22	1,17
Grid electricity & charging cost (€/kWh)	0,21	0,2	0,22
Green hydrogen (2023) (€/kg)	10,3	10,3	9,92
Green hydrogen (2030) (€/kg)	7,77	7,77	7,42
Green hydrogen (2040) (€/kg)	5,83	5,83	5,51
e-diesel (2023) (€/l)	2,51		
e-diesel (2030) (€/l)	2,22		
e-diesel (2035) (€/l)	2,24		
e-diesel (2040) (€/l)	2,23		
Bio-CNG (€/kg)	2,68		
HVO (€/l)	1,36		

Table 99. Weighted average fuel and energy retail prices in the EU. [4]

These retail prices from *Table 99* exclude the VAT as it is recoverable by fleets, but the levelized infrastructure cost dependent on the fuel as well as the fuel excise duties are included.

Table 100 shows the estimated hydrogen-at-the pump price in Spain, which is similar to green hydrogen retail prices from *Table 99*. As the values from this table are slightly higher and thus less optimistic, the selected green hydrogen retail prices for the studied years will be the prices from *Table 99*.

At-the-pump green hydrogen price in Spain (€/kg)				
	2022	2025	2030	2035
Spanish price	8,8	7,8	6,9	6

Table 100. At-the-pump green hydrogen price estimated for Spain in € for years 2022, 2025, 2030 and 2035. [44]

Table 101 shows the fuel and energy costs excluding VAT and recoverable taxes estimated in the EU. The diesel price is similar to the one proposed in *Table 99*. However, charging costs and the electricity grid prices proposed in *Table 101* are noticeably higher than what authors from *Table 99* propose (both *Tables 99* and *101* do include excise duties as they are non-recoverable in most of the EU countries).

Fuel and energy costs excluding VAT and recoverable taxes				
	2021	**2030**	**2040**	**2050**
Grid electricity (€/kWh)	0,127	0,118	0,095	0,073
Charging cost (€/kWh)	0,165	0,153	0,124	0,095
Diesel (€/l)	0,75 - 1,05 - 1,5			

Table 101. Fuel and energy costs excluding VAT and recoverable taxes for years 2021, 2030, 2040 and 2050. [5]

Table 102 shows that charging costs proposed by the authors of *Table 99* based on the 5-LH truck's daily driving ranges.

Charging costs (€/kWh)		
	2030	**2040**
5-LH (500 km)	0,123	0,12
5-LH (800 km)	0,123	0,12
5-LH (1000 km)	0,16	0,157

Table 102. Charging costs in €/kWh for 5-LH trucks based on their daily driving ranges in €/kWh for years 2030 and 2040. [4]

As it can be observed, *Table 102* charging costs are lower than the ones in *Table 101*. Moreover, according to [10] the Spanish retail prices at public recharging stations including receivable taxes are up to 0.5 €/kWh for chargers of 22 kW or lower and for chargers between 22 kW and 50 kW, between 0.36 and 0.69 €/kWh for chargers of between 50 kW and 250 kW and between 0.54 and 0.69 €/kWh for chargers of more than 250 kW.

Considering these prices after deducting the VAT and the estimates from *Tables 99, 101 and 102,* and bearing in mind that trucks with daily driving ranges of 500 km and 800 km charge 80% of the times at their deposits whereas 1,000 km daily driving range trucks charge always in public recharging stations, charging costs from *Table 99* will be multiplied by 1.2 for daily driving ranges of 500 km and 800 km, which provides average values among the reviewed literature.

For trucks with a daily driving range of 1,000 km the recharging costs will be estimated by computing the weighted average: 0.8 multiplied by 0.5 €/kWh (estimated retail price of the recharge in Spain excluding receivable taxes for chargers between 50 kW and 250 kW) and 0.2 multiplied by 0.26, which is an average recharge price for slow (22kW or less) and fast (between 22 and 50 kW) chargers. [10]

As several studies assume these values as constant, the same will be done in this report for the initial calculations of the OPEX and the TCO.

Table 103 summarizes the fuel and energy retail prices selected for further calculations in this report.

Selected weighted average fuel and energy retail prices			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Diesel (€/l)	1,22	1,22	1,17
Grid electricity & charging cost (€/kWh)	0,252	0,24	0,452
Green hydrogen (2023) (€/kg)	10,3	10,3	9,92
Green hydrogen (2030) (€/kg)	7,77	7,77	7,42
Green hydrogen (2040) (€/kg)	5,83	5,83	5,51
e-diesel (2023) (€/l)	2,51		
e-diesel (2030) (€/l)	2,22		
e-diesel (2035) (€/l)	2,24		
e-diesel (2040) (€/l)	2,23		
Bio-CNG (€/kg)	2,68		
HVO (€/l)	1,36		

Table 103. Weighted average fuel and energy retail prices for years 2023, 2030 and 2040 selected for this report. [4], [5], [10], [44]

3.2.2.1. FUEL CONSUMPTION

In order to compute the total fuel costs for the different trucks studies on this report it is necessary to know the fuel consumption for the different technologies. *Table 104* shows the truck's fuel consumption based on its technology and its driving range for years 2023, 2030 and 2040. [4]

Truck energy and fuel consumption based on technology and driving range				
Technology	Class	2023	2030	2040
Diesel/e-diesel/HVO (l/100 km)	5-LH (500 km)	30,7	23,2	23,2
	5-LH (800 km)	30,7	23,2	23,2
	5-LH (1000 km)	30,7	23,2	23,2
BET (kWh/100 km)	5-LH (500 km)	138	101	101
	5-LH (800 km)	141	103	103
	5-LH (1000 km)	141	108	108
FCET (kg/100 km)	5-LH (500 km)	8,32	6,13	5,82
	5-LH (800 km)	8,41	6,16	5,85
	5-LH (1000 km)	8,53	6,18	5,88
Bio-CNG (kg/100 km)	5-LH (500 km)	25,7	20,16	20,16
	5-LH (800 km)	25,79	20,35	20,35
	5-LH (1000 km)	26,25	20,66	20,66

Table 104. Truck energy and fuel consumption based on its technology and daily driving range for years 2023, 2030 and 2040. [4]

When it comes to the diesel, e-diesel and HVO truck's consumption, it can be seen that the values from *Table 104* are almost identic in comparison to values from *Table 105*.

Hence the diesel, e-diesel and HVO consumption from *Table 104* will be established for further calculations in this report.

Diesel average fuel consumption (l/100 km)		
	Long-haul	
	Low	Ref.
5-LH	26,17	34,42

Table 105. Diesel, e-diesel and HVO average fuel consumption for a 2016 long-haul truck. [5]

For the FCET's hydrogen consumption *Tables 106*, *107* and *108* show other authors' estimates, yet all of them have the same order of magnitude when compared among them and among *Table 104*. Hence, values from *Table 104* will be selected for this report when it comes to hydrogen consumption.

Hydrogen fuel consumption (kg/100 km)		
	2022	2030
5-LH (500 km)	9,04	6,64
5-LH (800 km)	9,13	6,69
5-LH (1000 km)	9,2	6,72

Table 106. Hydrogen fuel cell consumption in kg/100 km based on the truck's daily driving range for years 2022 and 2030. [39]

Hydrogen consumption for different fuel cell stack sizes		
	Fuel cell stack size (kW)	Hydrogen fuel consumption (kg/100 km)
2022 technology	180	9
	300	8,2
2030 technology	180	6,6
	300	6,3

Table 107. Hydrogen fuel consumption for fuel cell stacks of 300 kW and 180 kW (the selected size for this report) in kg/100 km for years 2022 and 2030. [44]

Fuel cell electric trucks weighted energy consumption			
	FCET (kg/100 km)		
	2022	2030	2040
5-LH	7,87	5,54	5,21

Table 108. Fuel cell electric trucks weighted energy consumption in kg/100 km for years 2022, 2030 and 2040. [5]

When it comes to the BET's energy consumption, the literature reviewed agrees on the order of magnitude of the energy consumption. An example of this is *Table 109*. As the consumption proposed by this author is slightly smaller than the one proposed in *Table*

104, the selected energy consumption for BETs in this report are the average values from *Tables 104* and *109*.

Battery electric trucks weighted energy consumption			
	BET (kWh/100 km)		
	2022	2030	2040
5-LH	124	91	91

Table 109. BETs weighted energy consumption in kWh/100 km for years 2022, 2030 and 2040. [5]

Table 110 summarizes the selected consumption values for computing the OPEX and the TCO in this report.

Truck energy and fuel consumption based on technology and driving range				
Technology	**Class**	**2023**	**2030**	**2040**
Diesel/e-diesel/HVO (l/100 km)	5-LH (500 km)	30,7	23,2	23,2
	5-LH (800 km)	30,7	23,2	23,2
	5-LH (1000 km)	30,7	23,2	23,2
BET (kWh/100 km)	5-LH (500 km)	131	96	96
	5-LH (800 km)	132,5	97	97
	5-LH (1000 km)	132,5	99,5	99,5
FCET (kg/100 km)	5-LH (500 km)	8,32	6,13	5,82
	5-LH (800 km)	8,41	6,16	5,85
	5-LH (1000 km)	8,53	6,18	5,88
Bio-CNG (kg/100 km)	5-LH (500 km)	25,7	20,16	20,16
	5-LH (800 km)	25,79	20,35	20,35
	5-LH (1000 km)	26,25	20,66	20,66

Table 110. Summary of the truck's energy and fuel consumption based on its technology and daily driving range for years 2023, 2030 and 2040. [4], [5], [39], [44]

Considering the unitary weighted average fuel and energy retail prices from *Table 103*, the fuel and energy consumption from *Table 110* and the kilometres travelled per year during the first five years of usage based on the truck's daily driving range the total fuel cost per year is obtained (*Table 111*). For computing the OPEX and the TCO it will be assumed that the fuel annual cost for the different technologies remains constant for the periods 2023-2029, 2030-2039 and 2040 onwards meaning that the annual fuel cost for 2023 equals that of 2025, for example.

Truck's energy and fuel annual consumption based on technology and driving range (€)				
Technology	**Class**	**2023**	**2030**	**2040**
Diesel	5-LH (500 km)	44.667	33.755	33.755
	5-LH (800 km)	59.308	44.819	44.819
	5-LH (1000 km)	72.357	54.680	54.680
BET	5-LH (500 km)	39.370	28.851	28.851
	5-LH (800 km)	50.355	36.864	36.864
	5-LH (1000 km)	120.645	90.598	90.598
FCET	5-LH (500 km)	102.200	56.803	40.465
	5-LH (800 km)	137.167	75.791	54.006
	5-LH (1000 km)	170.457	92.373	65.266
e-diesel	5-LH (500 km)	91.898	61.423	61.700
	5-LH (800 km)	122.019	81.556	81.924
	5-LH (1000 km)	155.227	103.752	104.219
Bio-CNG	5-LH (500 km)	82.141	64.434	64.434
	5-LH (800 km)	109.447	86.361	86.361
	5-LH (1000 km)	141.716	111.537	111.537
HVO	5-LH (500 km)	49.793	37.629	37.629
	5-LH (800 km)	66.114	49.962	49.962
	5-LH (1000 km)	84.107	63.560	63.560

Table 111. Truck's energy and fuel annual consumption based on its technology and daily driving range for years 2023, 2030 and 2040 established for this report in €. [4], [5], [10], [39], [44]

3.2.3. DRIVER WAGES AND INSURANCE

When it comes to labour costs, based on several papers that referenced difference sources including Comité National Routier (CNR) -organism that collects the average European labour costs-, it has been established that the driver's hourly rate for 5-LH trucks in addition to the driver's gross salary (including employer's social security benefits and the travel allowances) escalates to €25.56/hour *(Table 112)*. [4], [6]

As there are 52 weeks in a year and in Spain workers with a full-time job work 40 hours per week, the labour cost in this case would escalate to €53,164.80 per year.

Labour costs (€)			
	5-LH (500 km)	**5-LH (800 km)**	**5-LH (1000 km)**
Labor (€/hour)	25,56	25,56	25,56
Annual labour cost (€)	53.164,80	53.164,80	53.164,80

Table 112. Labour costs for a 5-LH truck based on its daily driving range for 2023 in €. [4], [6]

Moreover, a 0.8 % annual increase in response to the 2.5 % annual inflation rate assumed in this report will be considered *(Table 113)*. [43]

Labour costs (€)			
	2023	2030	2040
5-LH (500 km)	53.164,80	56.214,44	60.877,00
5-LH (800 km)			
5-LH (1000 km)			

Table 113. Labour costs for a 5-LH truck based on its daily driving range for 2023, 2030 and 2040 in €. [4], [6], [43]

Talking about the annual insurance fees, they are around 2% of the retail price in the reviewed literature. For example, they are assumed to be around 2% of the truck's CAPEX in paper [6], whereas in paper [4] the selected value is 2.14% of the truck's retail price as it is what the CNR establishes.

For calculating the OPEX and the TCO in this report, based on the data found and the sources backing it up, it has been decided to fix an annual insurance cost of 2.14% of the truck's retail price. The following tables show for each driving range the insurance cost depending on the 5-LH truck technology:

5-LH (500 km) truck's annual insurance cost (€)			
	2023	2030	2040
Diesel	1.733	1.904	1.904
HVO	1.733	1.904	1.904
BET	4.036	2.063	1.813
Bio-CNG	1.813	1.927	1.915
e-Diesel	1.733	1.904	1.904
FCET	5.540	2.223	1.995

Table 114. Annual insurance cost for 5-LH truck with 500 km daily driving range based on its technology for years 2023, 2030 and 2040. [4]

5-LH (800 km) truck's annual insurance cost (€)			
	2023	2030	2040
Diesel	3.766	4.109	4.109
HVO	3.766	4.109	4.109
BEV	9.780	4.751	4.323
Bio-CNG	4.023	4.259	4.237
e-Diesel	3.766	4.109	4.109
FCET	14.445	4.836	4.344

Table 115. Annual insurance cost for 5-LH truck with 800 km daily driving range based on its technology for years 2023, 2030 and 2040. [4]

5-LH (1000 km) truck's annual insurance cost (€)			
	2023	2030	2040
Diesel	3.766	4.109	4.109
HVO	3.766	4.109	4.109
BEV	9.780	5.115	4.665
Bio-CNG	4.023	4.280	4.237
e-Diesel	3.766	4.109	4.109
FCET	14.723	5.050	4.515

Table 116. Annual insurance cost for 5-LH truck with 1000 km daily driving range based on its technology for years 2023, 2030 and 2040. [4]

3.2.4. O&M (OPERATIONS AND MAINTENANCE)

When it comes to operations and maintenance costs (O&M) for 5-LH trucks, several papers agreed on the same figures as the average maintenance costs per 100 km for the first 5 years, which vary depending on the truck's technology *(Table 117)*. In the reviewed literature, maintenance costs are in general assumed to be constant for the 2023-2040 period except for the fuel cell technology, which is expected to suffer fluctuations in the maintenance costs. [4], [5], [8], [44]

Talking about e-diesel, HVO and CNG trucks, it is assumed that the maintenance cost for these technologies is the same as for diesel trucks. [4]

Between 2023 and 2030 the maintenance cost of FCET is expected to drop by 25.5% because of advanced new technologies, resulting in a maintenance cost of 13.78€/100km for this technology, which can be considered constant for the 2030-2040 period *(Table 117)*. [4], [5], [44]

The following table shows the O&M costs that will be used in this report for estimating the OPEX and the TCO based on the truck's technology and considering the expected decrease in maintenance costs for FCET by 2030. For the rest of technologies it will be assumed constant for the following decades as it is what the reviewed literature considers. [4], [5], [8], [44]

First five-year average maintenance cost							
Class	Diesel (€/100 km)	Bio-CNG (€/100 km)	Battery electric (€/100 km)	Fuel cell electric (2023) (€/100 km)	Fuel cell electric (+2030) (€/100 km)	e-Diesel (€/100 km)	HVO (€/100 km)
5-LH	18,5	18,5	13,24	18,5	13,78	18,5	18,5

Table 117. Five-year maintenance costs for 5-LH trucks depending on their technology. [4], [5], [8], [44]

As it can be observed in *Table 117*, battery electric trucks have the lowest maintenance costs followed by the maintenance costs of FCETs for 2030 onwards. Diesel, e-diesel, HVO and CNG technologies are considered to have the highest maintenance costs throughout the years and it is not expected for them to decrease. [5]

Considering the total kilometres travelled the first five years of the truck usage the total annual maintenance costs for this period are obtained based on the truck's technology. *Table 118* summarizes these total O&M costs.

First five-year average maintenance cost (€)							
Class	**Diesel**	**Bio-CNG**	**Battery electric**	**Fuel cell electric (2023)**	**Fuel cell electric (+2030)**	**e-Diesel**	**HVO (€/100 km)**
5-LH (500 km)	22.063	22.063	15.790	22.063	16.434	22.063	22.063
5-LH (800 km)	29.295	29.295	20.965	29.295	21.821	29.295	29.295
5-LH (1000 km)	37.267	37.267	26.671	37.267	27.759	37.267	37.267

Table 118. Total O&M annual average costs based on the truck's technology in € for 2023 and the following decades. [4], [5], [8], [44]

3.3. SUBSIDIES

In Spain, subsidies and tax exemptions have been implemented the last years with government plans such as MOVALT which provided between €2,500 and €18,000 of financial aid and was effective during 2017 and 2018 or the well know series of MOVES plans such as the MOVES II plan, which offered up to €15,000 of financial aid if buying trucks powered by alternative fuels. [11]

Moreover, €400 M were recently approved by the government with the objective of renewing the Spanish truck's fleet so that the number of alternatively powered trucks increases, which would reduce Tank to Wheel emissions. More information related to these government subsidies can be searched in *Real Decreto 983/2021*, later modified by the *Orden TMA/138/2022* and the *Real Decreto 188/2022*. [11], [53], [54]

The final recipients of this government plan are large companies, SMEs (Small and Medium Enterprises) and self-employed workers dedicated to professional transport. The financial aid amounts to €20,000 per zero-emission or low-emission truck and up to €200,000 depending on the type of company. Self-employed workers as well as small companies could receive this maximum, whereas the maximum mount for medium and large companies is of €175,000 and €150,000 respectively. Additionally, scrapping vehicles registered before 2019 implies an increase of up to €25,000 per vehicle. [11], [53] For this government plan BET, FCET, CNG, LNG and hybrid vehicles are the ones considered to being powered by alternative technologies. However, according to the *Real Decreto 983/2021,* for vehicles powered by gas it is additionally required that they belong to the N or M category and that they work on biomethane or other renewable gases. Moreover, biomethane should meet the sustainability and emission requirements gathered in the European Directive 2018/2001 (RED II). [11], [53], [55]

For estimating the TCO in this report a subsidy of €20,000 per truck will be considered for BET, FCET and CNG trucks which are the technologies studied that are included in the government financial aid plan, as it can be observed in *Table 119*. Moreover, it is assumed that this subsidy will be maintained for the following decades.

Spanish subsidies (€)			
	2023	2030	2040
FCET/BET/CNG	20.000	20.000	20.000
Diesel/e-diesel/HVO	0		

Table 119. Subsidies from the Spanish government based on the different trucks' technologies in € for years 2023, 2030 and 2040. [11], [53], [55]

3.4. SCRAPPAGE VALUE

Truck's residual value depends on the powertrain's technology as well as the truck's driving range.

For diesel, e-diesel, HVO and bio-CNG trucks the scrappage value after the first 5 years of operation has been estimated to be around 28% - 30% of its retail price for 2023 and it is expected to slightly decrease to 26% - 27% of its retail price for the 2030-2040 period for all daily driving ranges (500 km, 800 km and 1000 km). [4], [6], [44]

For these technologies the expected residual value is more certainly known and therefore less assumptions need to be made as e-diesel and HVO trucks almost share the same technology as diesel trucks -of which there is wide range of historic data- and bio-CNG technology is similar to the diesel one, being the storage tanks the most significant change as they both use an ICE engine.

However, BET and FCET use more innovative technology that is considerably less mature than the previous ones and therefore more assumptions on its current and future residual value need to be made.

In the case of BET and FCET its residual value is expected to increase over the next decades due to technological improvements such as the life expectancy increase of batteries and the fuel cell units. [4], [5], [44] BET's scrappage value is expected to increase from 21% in 2023 to 30% of the retail price by 2040 for a 500 km daily driving range, from 16% in 2023 to 33% of the retail price by 2040 for an 800 km daily driving range and from 14% in 2023 to 35% of the retail price by 2040 for a 1000 km daily driving range. [4]

FCET's residual value is expected to increase from 22% in 2023 to 33% of the retail price by 2040 for a 500 km daily driving range, from 19% in 2023 to 35% of the retail price by 2040 for an 800 km daily driving range and from 14% in 2023 to 35% of the retail price by 2040 for a 1000 km daily driving range. [4]

Tables 120, 121 and 122 show the truck's scrappage value depending on its technology and its driving range for 2023, 2030 and 2040. These are the values that will be selected for calculating the TCO in this report.

5-LH (500 km) truck's residual value (€)						
	2023		2030		2040	
Diesel	42.000	28%	43.000	26%	43.000	26%
HVO	42.000	28%	43.000	26%	43.000	26%
BET	76.000	21%	53.000	29%	47.000	30%
Bio-CNG	47.000	30%	46.000	27%	46.000	27%
e-Diesel	42.000	28%	43.000	26%	43.000	26%
FCET	106.000	22%	62.000	32%	58.000	33%

Table 120. Residual value of 5-LH trucks with a daily driving range of 500 km based on its technology for years 2023, 2030 and 2040 in €. [4]

5-LH (800 km) truck's residual value (€)						
	2023		2030		2040	
Diesel	48.000	27%	49.000	26%	49.000	26%
HVO	48.000	27%	49.000	26%	49.000	26%
BET	72.000	16%	71.000	32%	66.000	33%
Bio-CNG	55.000	29%	55.000	28%	55.000	28%
e-Diesel	48.000	27%	49.000	26%	49.000	26%
FCET	125.000	19%	75.000	33%	71.000	35%

Table 121. Residual value of 5-LH trucks with a daily driving range of 800 km based on its technology for years 2023, 2030 and 2040 in €. [4]

5-LH (1000 km) truck's residual value (€)						
	2023		2030		2040	
Diesel	48.000	27%	49.000	26%	49.000	26%
HVO	48.000	27%	49.000	26%	49.000	26%
BET	64.000	14%	81.000	34%	76.000	35%
Bio-CNG	55.000	29%	55.000	28%	55.000	28%
e-Diesel	48.000	27%	49.000	26%	49.000	26%
FCET	98.000	14%	79.000	33%	74.000	35%

Table 122. Residual value of 5-LH trucks with a daily driving range of 1000 km based on its technology for years 2023, 2030 and 2040 in €. [4]

3.5. DISCOUNT AND LIFETIME

The vast majority of the literature reviewed selected a discount rate of 9.5% for calculating the TCO [4], [5], [8], [56]. However, in source [6] a 7% was assumed as the discount rate.

Considering that most authors agree on a 9.5% discount rate, this is the value that will be used in this report for calculating the TCO.

Moreover, the truck ownership period chosen for estimating the TCO in this report is five years, which is on average the first user holding period. [4], [5], [8], [44], [56]

3.6. ANNUAL KM TRAVELLED

As previously stated, the truck ownership period for estimating the TCO in this report are the first five years, which corresponds to the average first user holding period.

According to the literature consulted, during the first five years of use the 5-LH truck's annual mileage on average is between 100.000 and 200.000 kilometres as it can be seen in *Table 123* and *Table 124*. [4], [5], [44]

When categorizing the 5-LH trucks depending on its daily driving range (500 km, 800 km and 1000 km) it can be observed that the five-year average annual mileage varies (*Table 124*). [4]

Truck annual mileage average during the first and second holding periods (km)				
Class	Reference annual mileage	First user (first 5 years)	Second user (last 10 years)	Lifetime mileage
5-LH	116.000	128.363	75.819	1.400.000

Table 123. 5-LH truck annual mileage average during the first and second holding periods in km. [5]

Truck annual mileage (km)						
Class	Five-year average annual milage	Year 1	Year 2	Year 3	Year 4	Year 5
5-LH (500 km)	119.259	130.297	130.279	120.506	109.962	105.252
5-LH (800 km)	158.349	173.000	173.000	160.000	146.000	139.747
5-LH (1000 km)	201.444	220.082	220.082	203.544	185.734	177.779

Table 124. 5-LH truck annual mileage during the first holding period (the first 5 years) based on the truck's daily driving range in km. [4]

In order to be consistent in this report the average annual mileage selected will be the one for the first five years of use and which subdivides the 5-LH tuck category according to daily driving range. Therefore, for calculating the TCO the annual mileages selected are: 119,259 km for 5-LH trucks with 500 km of driving range, 158,349 km for 5-LH trucks with 800 km of driving range and 201,444 km for 5-LH trucks with 1000 km driving range.

CHAPTER 4. Results

In the following sections, the results of computing the CAPEX, OPEX and TCO will be provided for years 2023, 2030 and 2040, depending on the trucks' daily driving range and its technology for different scenarios, starting with the *Base Case*.

Cases 1 and *2* are scenarios related to changes in parameters that affect BETs and FCETs, respectively. *Cases 3*, *4* and *5* imply parameter changes that affect the OPEX of diesel, battery electric and fuel cell trucks, respectively.

Moreover, it is considered that the fuel price and consumption of CNG trucks is that of CNG trucks fully running on biomethane (bio-CNG trucks), as it was explained in *Chapter 3*. Therefore, the computed OPEX and TCO results in this chapter are those of CNG trucks fully running on biomethane.

4.1. BASE CASE RESULTS

The inputs considered for the *Base Case* were previously explained in *Chapter 3. TCO calculations.* The CAPEX, OPEX and TCO results for years 2023, 2030 and 2040 will be provided based on the daily driving range and the truck's technology in the following sections.

4.1.1. CAPEX RESULTS

4.1.1.1. CAPEX RESULTS (500 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 500 km, *Tables 125, 126 and 127* show the results for the CAPEX for years 2023, 2030 and 2040.

CAPEX for each technology (500 km driving range) (€)				
	2023			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	297.365,20	76.953,65	80.601,08	454.919,92
BET	39.578,00	239.885,32	78.989,74	358.453,06
CNG	55.274,47	15.501,28	78.835,53	149.611,28
HVO	55.971,60	2.436,36	78.835,53	137.243,49
e-diesel	55.971,60	2.436,36	78.835,53	137.243,49
Diesel	55.971,60	2.436,36	78.835,53	137.243,49

Table 125. CAPEX for trucks with a 500 km daily driving range based on their technology in € for year 2023.

CAPEX for each technology (500 km driving range) (€)				
	2030			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	104.193,76	32.706,83	85.213,13	222.113,72
BET	21.248,90	78.018,41	82.908,87	182.176,18
CNG	65.703,97	11.982,33	88.050,10	165.736,40
HVO	66.532,64	2.896,06	88.050,10	157.478,81
e-diesel	66.532,64	2.896,06	88.050,10	157.478,81
Diesel	66.532,64	2.896,06	88.050,10	157.478,81

Table 126. CAPEX for trucks with a 500 km daily driving range based on their technology in € for year 2030.

CAPEX for each technology (500 km driving range) (€)				
	2040			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	90.363,34	27.480,38	102.077,90	219.921,62
BET	23.610,62	63.600,37	102.489,27	189.700,27
CNG	84.106,64	13.985,01	104.309,04	202.400,68
HVO	85.167,41	3.707,21	104.309,04	193.183,65
e-diesel	85.167,41	3.707,21	104.309,04	193.183,65
Diesel	85.167,41	3.707,21	104.309,04	193.183,65

Table 127. CAPEX for trucks with a 500 km daily driving range based on their technology in € for year 2040.

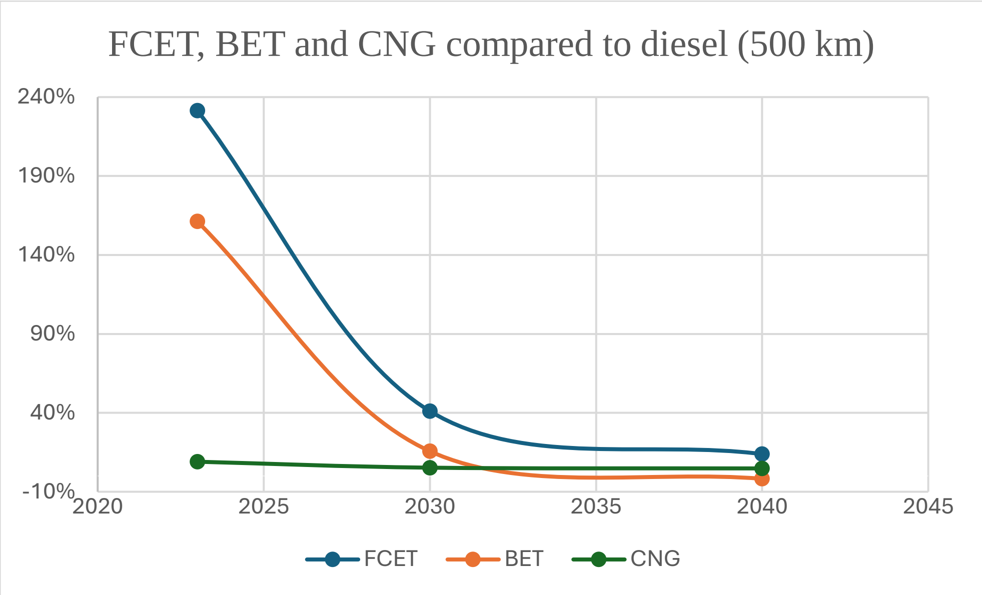

Figure 8. FCET, BET and CNG trucks CAPEXs compared to that of diesel trucks with a 500 km daily driving range for 2023, 2030 and 2040.

As it can be observed in *Table 125*, for year 2023 there is a considerable gap between FCETs and BETs compared to the rest of the technologies, being fuel cell trucks the most expensive ones. In contrast, the difference between CNG trucks and diesel, e-diesel and HVO trucks can be considered quite small, as it is around €12,000. This can also be seen in *Figure 8*, where FCETs and BETs have a CAPEX that is 231.5 % and 161.2 % higher than that of diesel trucks respectively while CNG trucks' CAPEX is only around 9 % higher.

The FCETs' CAPEX can be considered stabilized for 2030 and 2040 as both retail prices are around €220,000, which is slightly less than half of the CAPEX for year 2023 (there is a decrease of around 51.7 % between the 2023 CAPEX and the CAPEX for the following decades). As it can be observed, this is the technology for which a greater CAPEX reduction is expected from 2023 onwards.

While for FCETs the CAPEX for 2040 is lower than that of 2030, for the rest of technologies it is higher because the expected reductions in price for some FCETs' components compensate the effects of inflation, which does not occur for the rest of technologies.

For fuel cell trucks, the component that contributes the most to the 2023 and 2030 CAPEX is the powertrain, in which the fuel cell system is included. For 2040, as the fuel cell system retail price is expected to decrease notably compared to 2023, the rest of the truck component is the one contributing the most to the CAPEX for this year.

For BETs, the same occurs as with FECTs: the CAPEX can be considered constant for the following decades (around €185,000) and there is a 49.2 % and a 47.1 % reduction between the retail price in 2023 and the retail price in 2030 and in 2040 respectively. Between 2023 and 2040, the CAPEX decreases less than between 2023 and 2030 due to increases in the cost of the powertrain and the rest of the truck components derived from inflation. However, it can be observed that the energy storage (energy battery) reduces its costs from 2023 to 2040 non-stop.

Continuing with BETs, the most relevant component to the CAPEX is its energy storage system (energy battery in this particular case) for year 2023. Nevertheless, due to the estimated reductions in the battery price for the following decades, the rest of the truck cost is the one with the highest weight for the 2030 and 2040 CAPEXs for BETs.

In addition to this, the diesel, e-diesel, HVO and CNG CAPEXs values increase for the following decades as their powertrain, their energy storage systems and the rest of their truck components are mature technologies and consequently have been considered to be affected by inflation.

However, the difference in retail price between CNG and diesel, e-diesel and HVO technologies decrease for the following decades from around €12,000 in 2023 to €8,257.60 for 2030 and €9,217.03 for 2040.

For 2023 and 2030 the lowest CAPEX matches with diesel, e-diesel and HVO technologies, followed by CNG trucks, BETs and lastly FCETs. In *Figure 8* it can be observed that for 2030 FCETs and BETs are around 41 % and 15.7 % more expensive than diesel trucks in terms of CAPEX while CNG trucks' CAPEX is about 5.2 % higher.

However, for 2040, it is expected that BETs achieve the lowest CAPEX followed by diesel, e-diesel and HVO trucks, CNG and finally fuel cell trucks. In *Figure 8* it can be seen that while FCETs and CNG trucks are 13.8 % and 4.8 % more expensive than diesel trucks in terms of CAPEX, BETs are 1.8 % cheaper.

For 2040, it must be remarked that the retail price range between the different technologies is considerably smaller than that of 2023. In 2040 the lowest CAPEX is expected to be €193,183.65 and the highest one is estimated at €219,921.62, whereas for 2023 the lowest computed CAPEX is of €137,243.49 being the highest one of €454,919.92.

4.1.1.2. CAPEX RESULTS (800 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 800 km *Tables 128, 129 and 130* show the results for the CAPEX for years 2023, 2030 and 2040.

CAPEX for each technology (800 km driving range) (€)				
	2023			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	297.365,20	124.835,91	80.601,08	502.802,19
BET	39.578,00	368.351,83	78.989,74	486.919,57
CNG	55.274,47	20.073,60	78.835,53	154.183,60
HVO	55.971,60	3.480,51	78.835,53	138.287,64
e-diesel	55.971,60	3.480,51	78.835,53	138.287,64
Diesel	55.971,60	3.480,51	78.835,53	138.287,64

Table 128. CAPEX for trucks with an 800 km daily driving range based on their technology in € for year 2023.

CAPEX for each technology (800 km driving range) (€)				
	2030			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	104.193,76	53.520,26	85.213,13	242.927,16
BET	21.248,90	125.704,43	82.908,87	229.862,20
CNG	65.703,97	19.127,76	88.050,10	172.881,83
HVO	66.532,64	4.137,24	88.050,10	158.719,98
e-diesel	66.532,64	4.137,24	88.050,10	158.719,98
Diesel	66.532,64	4.137,24	88.050,10	158.719,98

Table 129. CAPEX for trucks with an 800 km daily driving range based on their technology in € for year 2030.

CAPEX for each technology (800 km driving range) (€)				
	2040			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	90.363,34	43.436,74	102.077,90	235.877,97
BET	23.610,62	102.473,87	102.489,27	228.573,76
CNG	84.106,64	22.324,70	104.309,04	210.740,37
HVO	85.167,41	5.296,01	104.309,04	194.772,45
e-diesel	85.167,41	5.296,01	104.309,04	194.772,45
Diesel	85.167,41	5.296,01	104.309,04	194.772,45

Table 130. CAPEX for trucks with an 800 km daily driving range based on their technology in € for year 2040.

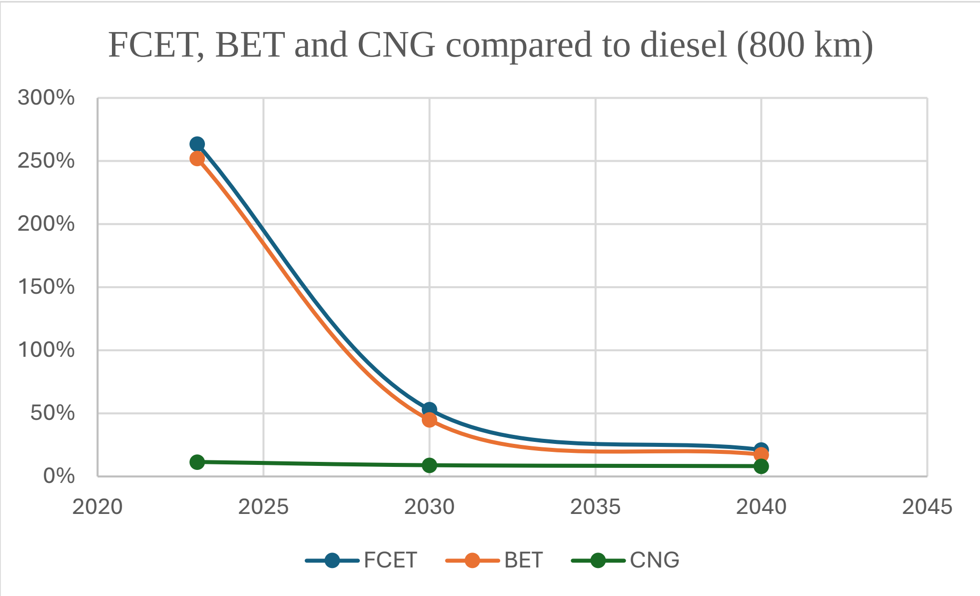

Figure 9. FCET, BET and CNG trucks CAPEXs compared to that of diesel trucks with an 800 km daily driving range for 2023, 2030 and 2040.

As shown in *Table 128*, for year 2023 there is a considerable gap between FCETs and BETs compared to the other technologies, being fuel cell trucks the most expensive ones. This gap is larger for trucks with a daily driving range of 800 km than for trucks with a 500 km daily driving range. In this case, the difference between CNG trucks and diesel, e-diesel and HVO trucks is around €16,000, which can be considered not significant when compared to the differences in CAPEX between these technologies and electric or fuel-cell trucks.

This gap can also be observed in *Figure 9*, where FCETs and BETs have a CAPEX that is 263.6 % and 252.1 % higher than that of diesel trucks respectively while CNG trucks' CAPEX is only around 11.5 % higher.

The FCETs' CAPEX can be considered constant for 2030 and 2040, being around €238,000 (€242,927.16 for 2030 and €235,877.97 for 2040), which implies a decrease of around 51.7 % for the 2023-2030 period and of around 53.1 % for the 2023-2040 period. As it can be observed, for trucks with an 800 km daily driving range, FCETs as well as BETs, are the ones for which a greater CAPEX reduction is expected in the following decades.

When it comes to fuel cell trucks, the component with the highest weight in the CAPEX for years 2023 and 2030 is the powertrain, in which the fuel cell system is accounted for. For 2040, as the fuel cell system retail price is expected to decrease considerably compared to the 2023 price, the rest of the truck component's cost is the one contributing the most to the CAPEX.

For the BETs the same happens as with FECTs: the CAPEX can be considered constant for the following decades (around €229,000) and there is approximately a 52.8 % and a 53.1 % reduction between the retail price in the 2023-2030 period and the retail price in the 2023-2040 period respectively. In contrast to what happened for BETs with a daily driving range of 500 km, the CAPEX decreases non-stop throughout the 2023-2040 period as the reduction in the cost of the energy battery exceeds the effects that inflation has on the mature components of the truck (the powertrain and the rest of the truck components).

Talking about battery electric trucks, the energy storage component (energy battery) contributes the most to the CAPEX for years 2023 and 2030. However, as significant reductions in the battery price are expected for the following decades, it can be observed in the previous tables how the energy storage cost becomes closer to the rest of the truck cost for the following decades, being slightly below it for 2040.

Moreover, the diesel, e-diesel, HVO and CNG CAPEXs values increase for the following decades as the powertrain, the energy storage systems and the rest of the truck components are mature technologies and therefore they have been considered to be affected by inflation.

Nevertheless, the differences in retail price between CNG and diesel, e-diesel and HVO technologies can be considered stable throughout the 2023-2040 period as those variations between the CAPEX of these technologies are of €15,895.96 for 2023 of €14,161.85 for 2030 and of €15,967.92 for 2040. This can be explained mainly by the fact that the CNG tank price for trucks with a daily driving range of 800 km fluctuates less during the studied period than that for trucks with a 500 km daily driving range.

For 2023, the lowest CAPEX corresponds to diesel, e-diesel and HVO technologies, followed by CNG trucks, BETs and lastly FCETs. This dynamic is maintained for 2030 and 2040 as opposed to what happened for trucks with a 500 km daily driving range. *Figure 9* shows that FCETs, BETs and CNG trucks have higher CAPEXs than diesel (53.1%, 44.8 % and 8.9 % respectively for 2030 and 21.1 %, 17.4 % and 8.2 % for 2040).

Despite FCETs and BETs being the most expensive technologies throughout the 2023-2040 period, it must be acknowledged that the retail price range between the different technologies is considerably smaller than that of 2023. In 2040 the lowest CAPEX is expected to be €194,772.45 and the highest one is estimated at €235,877.97, whereas for 2023 the lowest computed CAPEX is of €138,287.64 being the highest one of €502,802.19.

4.1.1.3. CAPEX RESULTS (1,000 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 1,000 km *Tables 131, 132 and 133* show the results for the CAPEX for years 2023, 2030 and 2040.

CAPEX for each technology (1000 km driving range) (€)				
	2023			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	297.365,20	147.066,97	80.601,08	525.033,24
BET	39.578,00	442.935,47	78.989,74	561.503,20
CNG	55.274,47	20.073,60	78.835,53	154.183,60
HVO	55.971,60	4.176,61	78.835,53	138.983,74
e-diesel	55.971,60	4.176,61	78.835,53	138.983,74
Diesel	55.971,60	4.176,61	78.835,53	138.983,74

Table 131. CAPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2023.

CAPEX for each technology (1000 km driving range) (€)				
	2030			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	104.193,76	65.413,66	85.213,13	254.820,55
BET	21.248,90	159.536,71	82.908,87	263.694,48
CNG	65.703,97	19.787,34	88.050,10	173.541,41
HVO	66.532,64	4.964,68	88.050,10	159.547,42
e-diesel	66.532,64	4.964,68	88.050,10	159.547,42
Diesel	66.532,64	4.964,68	88.050,10	159.547,42

Table 132. CAPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2030.

CAPEX for each technology (1000 km driving range) (€)				
	2040			
	Powertrain	Energy storage	Rest of the truck	CAPEX
FCET	90.363,34	54.074,30	102.077,90	246.515,54
BET	23.610,62	130.053,84	102.489,27	256.153,74
CNG	84.106,64	23.094,51	104.309,04	211.510,19
HVO	85.167,41	6.355,21	104.309,04	195.831,66
e-diesel	85.167,41	6.355,21	104.309,04	195.831,66
Diesel	85.167,41	6.355,21	104.309,04	195.831,66

Table 133. CAPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2040.

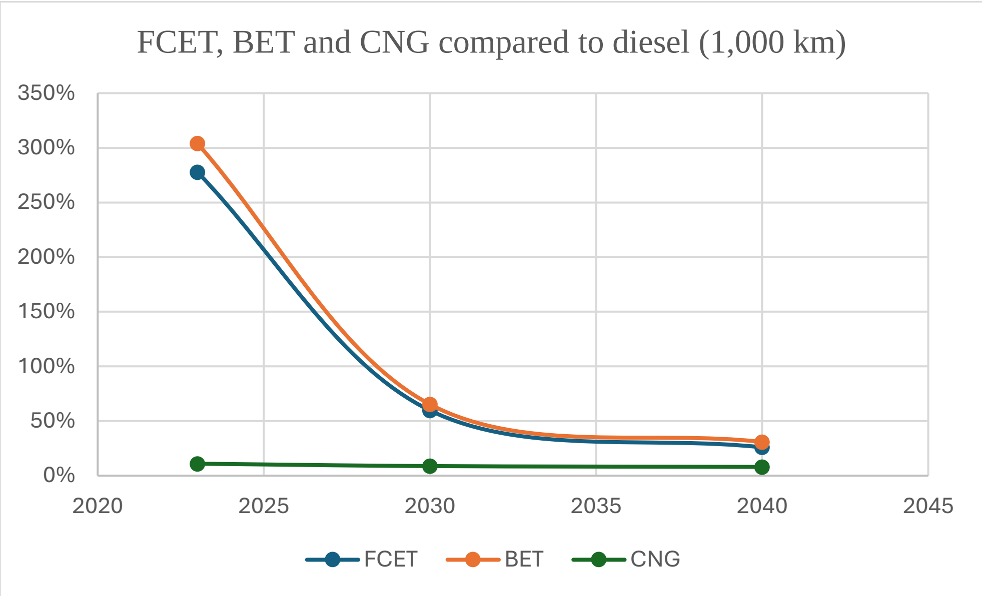

Figure 10. FCET, BET and CNG trucks CAPEXs compared to that of diesel trucks with a 1,000 km daily driving range for 2023, 2030 and 2040.

As it can be observed in *Table 131*, for year 2023 there is a noticeable gap between FCETs and BETs in comparison to the rest of technologies, being battery electric trucks the most expensive ones. For the trucks with a daily driving range of 1,000 km this gap is considerably larger compared to the other daily driving ranges studied. This gap can also be seen in *Figure 10*, where FCETs and BETs are 277.8 % and 304 % more expensive than diesel trucks.

Moreover, it is noticeable that whereas for 1,000 km daily driving ranges the most expensive CAPEX is that of BETs, for trucks with 500 km and 800 km daily driving ranges FCETs have the most expensive one. For this driving range (1,000 km), the difference between CNG trucks and diesel, e-diesel and HVO trucks is around €15,000 (11 %), which can be considered relatively small in comparison to the differences in CAPEX between these technologies and electric or fuel-cell trucks.

The FCETs' CAPEX can be considered stabilized for 2030 and 2040 as both retail prices are around €250,000 (€254,820.55 for 2030 and €246,515.54 for 2040), which is slightly less than half of the CAPEX for year 2023 (there is a decrease of around 51.5 % between 2023 and 2030 and of approximately 53 % between 2023 and 2040). These CAPEX reductions are similar to the ones of fuel cell trucks with daily driving ranges of 500 km and 800 km.

Talking about fuel cell trucks, the powertrain, where the fuel cell system is included, is the component that has the highest weight for the 2023 and 2030 CAPEXs. However, as the fuel cell system retail price is expected to decrease notably throughout the 2023-2040, the rest of the truck cost is the one contributing the most to the CAPEX for year 2040.

For the BETs the same occurs as with FECTs: the CAPEX can be considered constant for the following decades (around €260,000) and there is around a 53 % and a 54.4 % reduction between the retail price in 2023 and the retail price in 2030 and in 2040 respectively.

Along whit what occurred for BETs with a daily driving range of 800 km, the CAPEX decreases non-stop throughout the 2023-2040 period as the reduction in the cost of the energy battery is higher than the effects that inflation has on the mature components of the truck (the powertrain and the rest of the truck components). Additionally, for this daily driving range BETs are the technology whose CAPEX is expected to decrease the most during the analysed period.

For battery electric trucks, the energy storage component (energy battery) contributes the most to the CAPEX for years 2023, 2030 and 2040. Despite significant reductions in the battery price for the following decades, the energy storage cost continues to have the highest weight on the CAPEX, although as it is shown in the previous tables, the energy storage cost becomes closer to the rest of the truck cost throughout the studied period.

Additionally, the diesel, e-diesel, HVO and CNG CAPEXs values increase for the following decades as the powertrain, the energy storage systems and the rest of the truck components are mature technologies and in consequence have been considered to be affected by inflation.

However, the differences in retail price between CNG and diesel, e-diesel and HVO technologies can be considered stable throughout the 2023-2040 period as although there are some fluctuations, these differences are close to €15,000 for the studied years (the differences in retail price between these technologies are of €15,199.85 for 2023, of €13,993.99 for 2030 and of €15,678.53 for 2040). These variations along the years are mainly caused due to small variations in the CNG and the diesel tank prices.

For the 2023-2040 period, the lowest CAPEX is linked to diesel, e-diesel and HVO technologies, followed by CNG trucks, FCETs and finally BETs. It is noticeable that for trucks with a 1,000 km daily driving range the most expensive technology is the battery electric one, whereas for the shorter daily driving ranges studied previously the highest

CAPEX belongs to fuel-cell trucks. *Figure 10* shows that FCETs, BETs and CNG trucks have higher CAPEXs than diesel (59.7 %, 65.3 % and 8.8 % respectively for 2030 and 25.9 %, 30.8 % and 8 % for 2040).

Despite FCETs and BETs being the most expensive technologies throughout the 2023-2040 period, it must be taken into consideration that the retail price range between the different technologies considerably reduces between 2023 and 2040. In 2040 the lowest CAPEX is expected to be €195,831.66 and the highest one is estimated at €256,153.74, whereas for 2023 the lowest computed CAPEX is of €138,983.74 being the highest one of €561,503.20.

4.1.2. OPEX RESULTS

4.1.2.1. OPEX RESULTS (500 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 500 km *Tables 134, 135 and 136* show the results for the OPEX for years 2023, 2030 and 2040. OPEX_1 corresponds to the trucks' OPEXs considering the CO_2 road fees that the European Parliament has already approved and are supposed to be applied in the different European member states from 2023 onwards. OPEX_2 refers to the trucks' OPEXs without applying such CO_2 road fees as there are member states which are postponing this measure.

OPEX for each technology (500 km driving range) (€)								
	2023							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	7.632,59	-	102.200,36	53.164,80	5.540,00	22.062,95	190.600,70	190.600,70
BET	7.632,59	-	39.369,85	53.164,80	4.036,00	15.789,92	119.993,15	119.993,15
CNG	15.265,18	9.540,74	82.140,97	53.164,80	1.813,00	22.062,95	183.987,63	174.446,90
HVO	15.265,18	9.540,74	49.793,10	53.164,80	1.733,00	22.062,95	151.559,77	142.019,03
e-diesel	15.265,18	9.540,74	91.897,56	53.164,80	1.733,00	22.062,95	193.664,23	184.123,49
Diesel	15.265,18	9.540,74	44.667,34	53.164,80	1.733,00	22.062,95	146.434,01	136.893,27

Table 134. OPEX for trucks with a 500 km daily driving range based on their technology in € for year 2023.

OPEX for each technology (500 km driving range) (€)								
	2030							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	7.632,59	-	56.803,28	56.214,44	2.223,00	16.433,92	139.307,23	139.307,23
BET	7.632,59	-	28.851,19	56.214,44	2.063,00	15.789,92	110.551,14	110.551,14
CNG	15.265,18	9.540,74	64.434,31	56.214,44	1.927,00	22.062,95	169.444,62	159.903,89
HVO	15.265,18	9.540,74	37.628,66	56.214,44	1.904,00	22.062,95	142.615,97	133.075,24
e-diesel	15.265,18	9.540,74	61.423,26	56.214,44	1.904,00	22.062,95	166.410,57	156.869,83
Diesel	15.265,18	9.540,74	33.755,12	56.214,44	1.904,00	22.062,95	138.742,43	129.201,70

Table 135. OPEX for trucks with a 500 km daily driving range based on their technology in € for year 2030.

OPEX for each technology (500 km driving range) (€)								
	2040							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	7.632,59	-	40.465,36	60.877,00	1.995,00	16.433,92	127.403,87	127.403,87
BET	7.632,59	-	28.851,19	60.877,00	1.813,00	15.789,92	114.963,69	114.963,69
CNG	15.265,18	9.540,74	64.434,31	60.877,00	1.915,00	22.062,95	174.095,18	164.554,44
HVO	15.265,18	9.540,74	37.628,66	60.877,00	1.904,00	22.062,95	147.278,53	137.737,79
e-diesel	15.265,18	9.540,74	61.699,94	60.877,00	1.904,00	22.062,95	171.349,80	161.809,07
Diesel	15.265,18	9.540,74	33.755,12	60.877,00	1.904,00	22.062,95	143.404,99	133.864,25

Table 136. OPEX for trucks with a 500 km daily driving range based on their technology in € for year 2030.

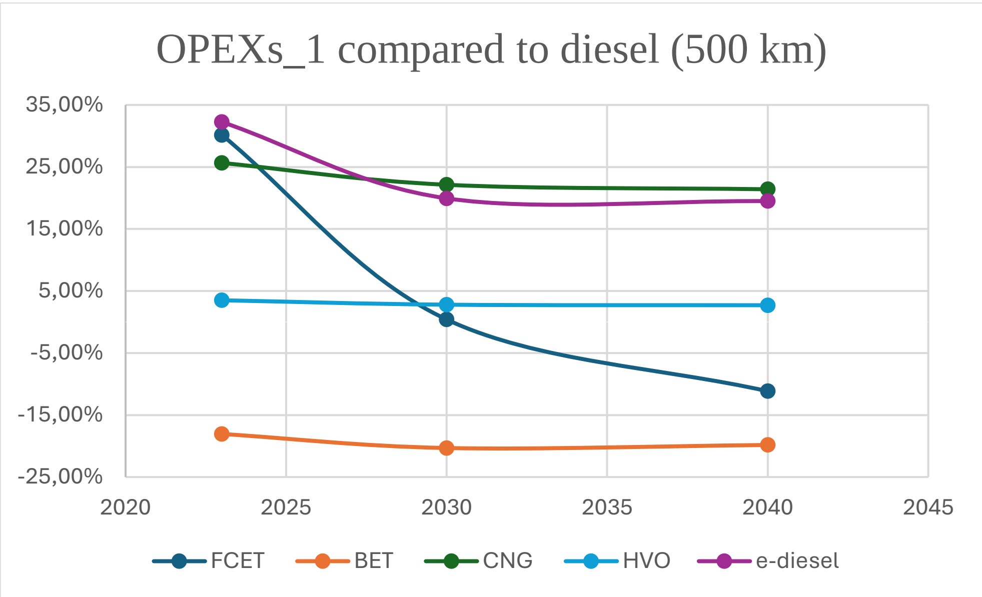

Figure 11. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_1 compared to that of diesel trucks with a 500 km daily driving range for 2023, 2030 and 2040.

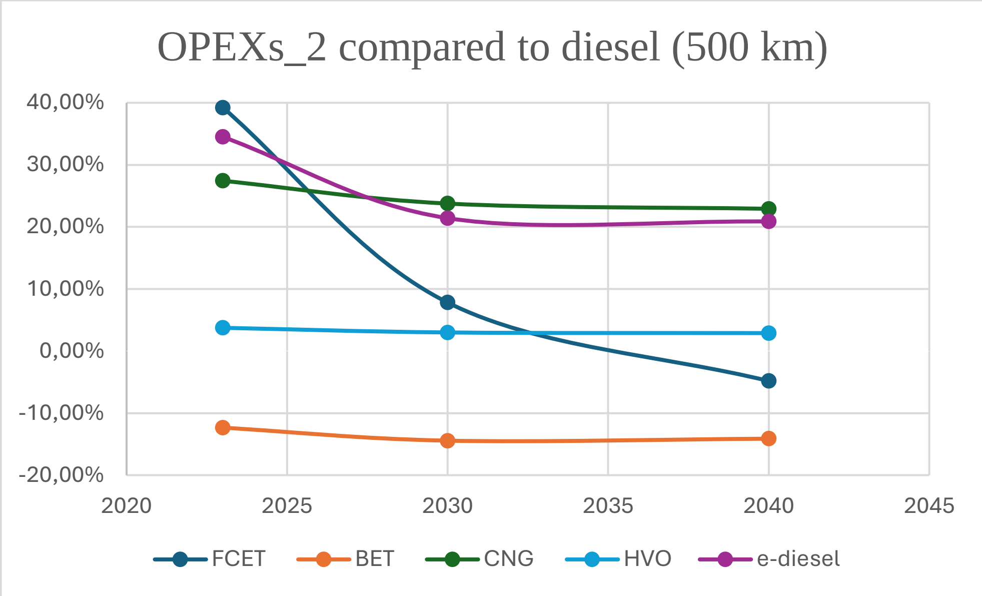

Figure 12. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_2 compared to that of diesel trucks with a 500 km daily driving range for 2023, 2030 and 2040.

As can be observed in *Tables 134, 135 and 136*, introducing CO_2 road fees has a negative impact on the OPEX of all technologies except for fuel-cell and battery electric trucks, which are the only ones exempted from these charges. Applying these fees is the formula used by the EU to make zero-emission technologies (BETs and FCETs) more competitive against CNG, HVO, diesel, and e-diesel trucks.

Another measure taken by the EU to encourage consumers to purchase zero-emission trucks is the 50 % reduction applied in road tolls for these technologies which positively affects their OPEX and consequently their TCO value. This measure is applied for both, OPEX_1 and OPEX_2.

Focussing on the year 2023, the highest OPEX_1 corresponds to e-diesel trucks closely followed by FCETs and CNG trucks. However, the highest OPEX_2 (no CO_2 fees considered) is that of FCETs followed by e-diesel and CNG trucks. Next on the ranking, the OPEX_1 and OPEX_2 of HVO and diesel trucks appear, with both being similar, yet the diesel one is slightly lower in both scenarios. Finally, BETs have the lowest OPEX in both cases, which is 18.1 % and 12.4 % lower than OPEX_1 and OPEX_2 of diesel trucks (*Figures 11 and 12*).

For years 2030 and 2040, the OPEX ranking changes mainly due to variations in the expected fuel consumption, the fuel prices and the operation and maintenance costs of the different technologies.

In 2030, CNG trucks have the highest OPEX_1 and OPEX_2, being closely followed by e-diesel trucks in both cases. The next positions for OPEX_1 are occupied by HVO, fuel cell and diesel trucks in that order. For OPEX_2, the next places correspond to fuel cell, HVO and diesel trucks. Finally, as in 2023, BETs have the lowest OPEX, regardless of whether CO_2 charges are considered, which is 20.3 % and 14.4 % lower than OPEX_1 and OPEX_2 of diesel trucks respectively as it can be seen in *Figures 11 and 12*.

Referring to the year 2040, CNG trucks have the highest OPEX_1 and OPEX_2 for this year, closely followed by e-diesel trucks. The next positions correspond to HVO, diesel and fuel cell trucks in that order in both cases (with and without CO_2 fees applied) and once more, BETs have the lowest OPEX for both scenarios. For 2040, BETs and FCETs have an OPEX_1 which is 19.8 % and 11.2 % lower than that of diesel trucks respectively and an OPEX_2 that is 4.8 % and 14.1 % lower (*Figures 11 and 02*).

It is remarkable that while BETs have the lowest OPEX with or without considering CO_2 charges for the 2023-2040 period, this European measure does have an impact on the position of FCETs in comparison to other technologies in terms of OPEX for years 2023 and 2030 talking about trucks with a 500 km daily driving range. Nevertheless, for 2040, fuel cell trucks have the second lowest OPEX in both scenarios.

From the previous analysis, it can be deduced that in the following decades, based on the estimates currently made by the scientific community, CNG and e-diesel technologies will not be able to compete in terms of OPEX with HVO, diesel, fuel cell and battery electric trucks. Additionally, from the four technologies previously mentioned the battery electric one has been predicted to be the most competitive one in terms of OPEX.

4.1.2.2. OPEX Results (800 km daily driving range)

For trucks with a daily driving range of 800 km *Tables 137,138 and 139* show the results for the OPEX for years 2023, 2030 and 2040.

OPEX for each technology (800 km driving range) (€)								
	2023							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	11.401,16	-	137.167,00	53.164,80	14.445,00	29.294,64	245.472,60	245.472,60
BET	11.401,16	-	50.355,11	53.164,80	9.780,00	20.965,46	145.666,53	145.666,53
CNG	22.802,31	12.667,95	109.446,67	53.164,80	4.023,00	29.294,64	231.399,38	218.731,42
HVO	22.802,31	12.667,95	66.114,04	53.164,80	3.766,00	29.294,64	187.809,75	175.141,79
e-diesel	22.802,31	12.667,95	122.019,30	53.164,80	3.766,00	29.294,64	243.715,00	231.047,05
Diesel	22.802,31	12.667,95	59.308,18	53.164,80	3.766,00	29.294,64	181.003,89	168.335,94

Table 137. OPEX for trucks with an 800 km daily driving range based on their technology in € for year 2023.

OPEX for each technology (800 km driving range) (€)								
	2030							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	11.401,16	-	75.791,09	56.214,44	4.836,00	21.820,55	170.063,24	170.063,24
BET	11.401,16	-	36.863,74	56.214,44	4.751,00	20.965,46	130.195,80	130.195,80
CNG	22.802,31	12.667,95	86.360,60	56.214,44	4.259,00	29.294,64	211.598,94	198.930,99
HVO	22.802,31	12.667,95	49.962,40	56.214,44	4.109,00	29.294,64	175.050,75	162.382,80
e-diesel	22.802,31	12.667,95	81.556,27	56.214,44	4.109,00	29.294,64	206.644,62	193.976,67
Diesel	22.802,31	12.667,95	44.819,21	56.214,44	4.109,00	29.294,64	169.907,56	157.239,61

Table 138. OPEX for trucks with an 800 km daily driving range based on their technology in € for year 2030.

OPEX for each technology (800 km driving range) (€)								
	2040							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	11.401,16	-	54.005,85	60.877,00	4.344,00	21.820,55	152.448,56	152.448,56
BET	11.401,16	-	36.863,74	60.877,00	4.323,00	20.965,46	134.430,36	134.430,36
CNG	22.802,31	12.667,95	86.360,60	60.877,00	4.237,00	29.294,64	216.239,50	203.571,55
HVO	22.802,31	12.667,95	49.962,40	60.877,00	4.109,00	29.294,64	179.713,31	167.045,35
e-diesel	22.802,31	12.667,95	81.923,65	60.877,00	4.109,00	29.294,64	211.674,55	199.006,60
Diesel	22.802,31	12.667,95	44.819,21	60.877,00	4.109,00	29.294,64	174.570,12	161.902,17

Table 139. OPEX for trucks with an 800 km daily driving range based on their technology in € for year 2040.

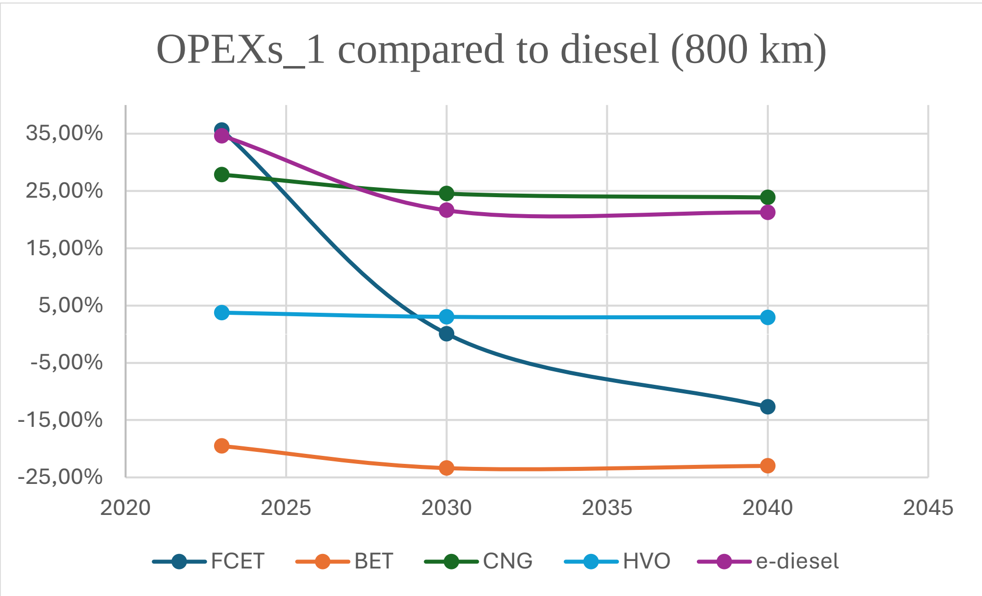

Figure 13. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_1 compared to that of diesel trucks with an 800 km daily driving range for 2023, 2030 and 2040.

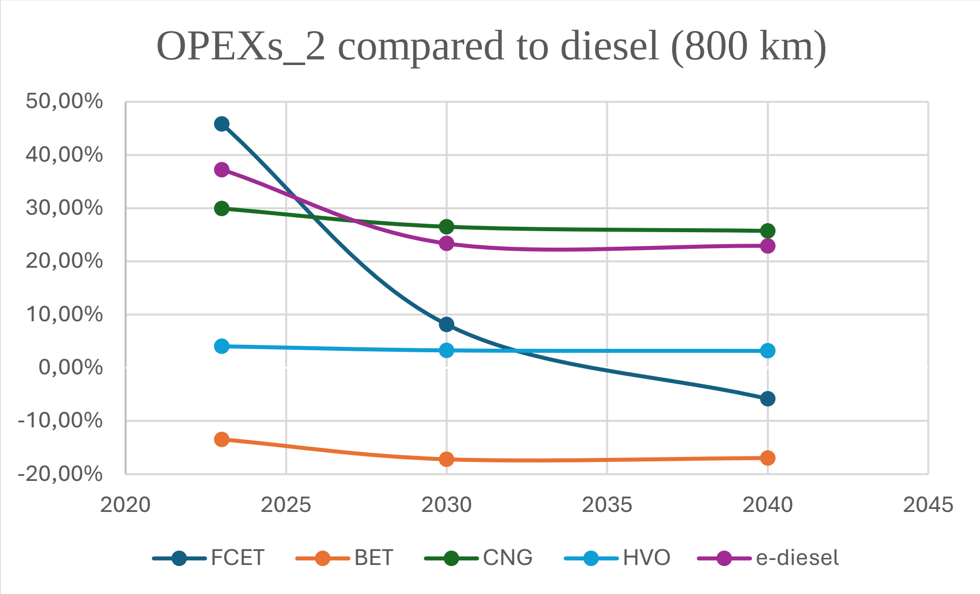

Figure 14. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_2 compared to that of diesel trucks with an 800 km daily driving range for 2023, 2030 and 2040.

Beginning the analysis by studying year 2023, the highest OPEX_1 and OPEX_2 correspond to FCETs, being closely followed by e-diesel trucks. The next positions on both rankings are held by CNG, HVO and diesel trucks in this order. Finally, BETs have the lowest OPEX in both cases, which is 19.5 % and 13.5 % lower than OPEX_1 and OPEX_2 of diesel trucks (*Figures 13 and 14*). In contrast to what happened at the same year for trucks with a 500 km daily driving range, for trucks with 800 km daily driving ranges applying the CO_2 road charges do not stop the FCETs' OPEX to be the highest one.

As it occurred for the 500 km daily driving range trucks, for years 2030 and 2040 the OPEX ranking will vary mainly due to changes in the expected fuel consumption, the fuel prices and the operation and maintenance costs of the different technologies.

For year 2030, CNG trucks have the highest OPEX_1 and OPEX_2, being closely followed by e-diesel trucks in both scenarios. For OPEX_1 the next positions are held by HVO, fuel cell and diesel trucks respectively. When it comes to OPEX_2, the next places correspond to fuel cell, HVO and diesel trucks in that order. Lastly, as it happened in 2023, BETs have the lowest OPEX whether CO_2 charges are considered or not, which is 23.4 % and 17.2 % lower than OPEX_1 and OPEX_2 of diesel trucks as it can be seen in *Figures 13 and 14*. It is noticeable that despite the OPEX values being different, the OPEX rankings for both, trucks with 500 km and 800 km daily driving ranges, are the same in terms of the positioning of the different technologies.

When it comes to year 2040, the highest OPEX_1 and OPEX_2 corresponds to CNG trucks, closely followed by e-diesel ones. The next positions of the ranking for both, OPEX_1 and OPEX_2, are held by HVO, diesel and fuel-cell trucks. Once more, battery electric trucks are the ones with the lowest OPEX for both scenarios. For 2040, BETs and FCETs have an OPEX_1 which is 23 % and 12.7 % lower than that of diesel trucks respectively and an OPEX_2 that is 17 % and 5.8 % lower (*Figures 13 and 14*). Moreover, it is noticeable that the 2040 OPEX rankings follow the same order for trucks with 500 km and 800 km daily driving ranges.

It is needed to acknowledge that as BETs have the lowest OPEX with or without taking into account CO_2 fees for the 2023-2040 period, this European measure only has an impact on the position of FCETs in the OPEX ranking for year 2030. However, for 2023 and 2040 it does help make FCETs more competitive in terms of OPEX against other technologies. This suggests that, if predictions from the experts are accurate, this measure would not have such a great impact on the OPEX zero-emission trucks, especially when focussing on BETs for the studied daily driving range.

From the analysis made, the same can be deduced as for trucks with 500 km daily driving ranges: if the predictions made by analysts are correct, CNG and e-diesel technologies will not be competitive in terms of OPEX with HVO, diesel, fuel cell and battery electric trucks for the following decades. Moreover, when it comes to the OPEX value, BETs have been estimated to be the most competitive technology throughout the whole 2023-2040 period.

4.1.2.3. OPEX RESULTS (1,000 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 1,000 km *Tables 140,141 and 142* show the results for the OPEX for years 2023, 2030 and 2040.

OPEX for each technology (1000 km driving range) (€)								
	2023							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	15.309,76	-	170.457,25	53.164,80	14.723,00	37.267,18	290.921,98	290.921,98
BET	15.309,76	-	120.644,93	53.164,80	9.780,00	26.671,21	225.570,70	225.570,70
CNG	30.619,52	16.115,54	141.715,99	53.164,80	4.023,00	37.267,18	282.906,03	266.790,49
HVO	30.619,52	16.115,54	84.106,98	53.164,80	3.766,00	37.267,18	225.040,01	208.924,48
e-diesel	30.619,52	16.115,54	155.226,86	53.164,80	3.766,00	37.267,18	296.159,89	280.044,35
Diesel	30.619,52	16.115,54	72.356,74	53.164,80	3.766,00	37.267,18	213.289,77	197.174,24

Table 140. OPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2023.

OPEX for each technology (1000 km driving range) (€)								
	2030							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	15.309,76	-	92.373,45	56.214,44	5.050,00	27.759,01	196.706,66	196.706,66
BET	15.309,76	-	90.597,51	56.214,44	5.115,00	26.671,21	193.907,93	193.907,93
CNG	30.619,52	16.115,54	111.537,24	56.214,44	4.280,00	37.267,18	256.033,91	239.918,37
HVO	30.619,52	16.115,54	63.559,67	56.214,44	4.109,00	37.267,18	207.885,35	191.769,81
e-diesel	30.619,52	16.115,54	103.751,82	56.214,44	4.109,00	37.267,18	248.077,49	231.961,96
Diesel	30.619,52	16.115,54	54.680,01	56.214,44	4.109,00	37.267,18	199.005,69	182.890,15

Table 141. OPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2030.

OPEX for each technology (1000 km driving range) (€)								
	2040							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
FCET	15.309,76	-	65.265,50	60.877,00	4.515,00	27.759,01	173.726,27	173.726,27
BET	15.309,76	-	90.597,51	60.877,00	4.665,00	26.671,21	198.120,48	198.120,48
CNG	30.619,52	16.115,54	111.537,24	60.877,00	4.237,00	37.267,18	260.653,47	244.537,93
HVO	30.619,52	16.115,54	63.559,67	60.877,00	4.109,00	37.267,18	212.547,90	196.432,37
e-diesel	30.619,52	16.115,54	104.219,17	60.877,00	4.109,00	37.267,18	253.207,40	237.091,87
Diesel	30.619,52	16.115,54	54.680,01	60.877,00	4.109,00	37.267,18	203.668,24	187.552,71

Table 142. OPEX for trucks with a 1,000 km daily driving range based on their technology in € for year 2040.

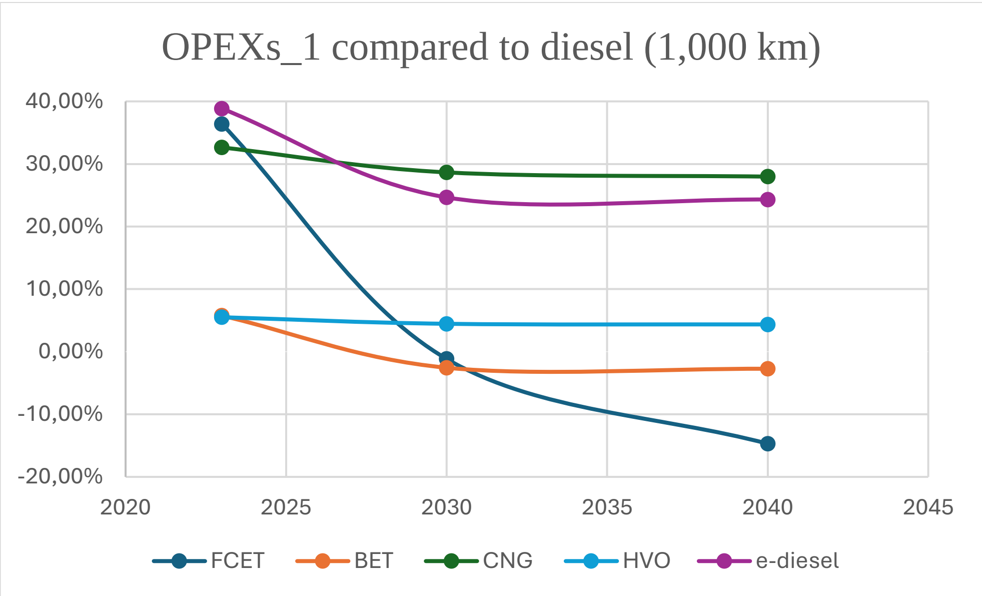

Figure 15. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_1 compared to that of diesel trucks with a 1,000 km daily driving range for 2023, 2030 and 2040.

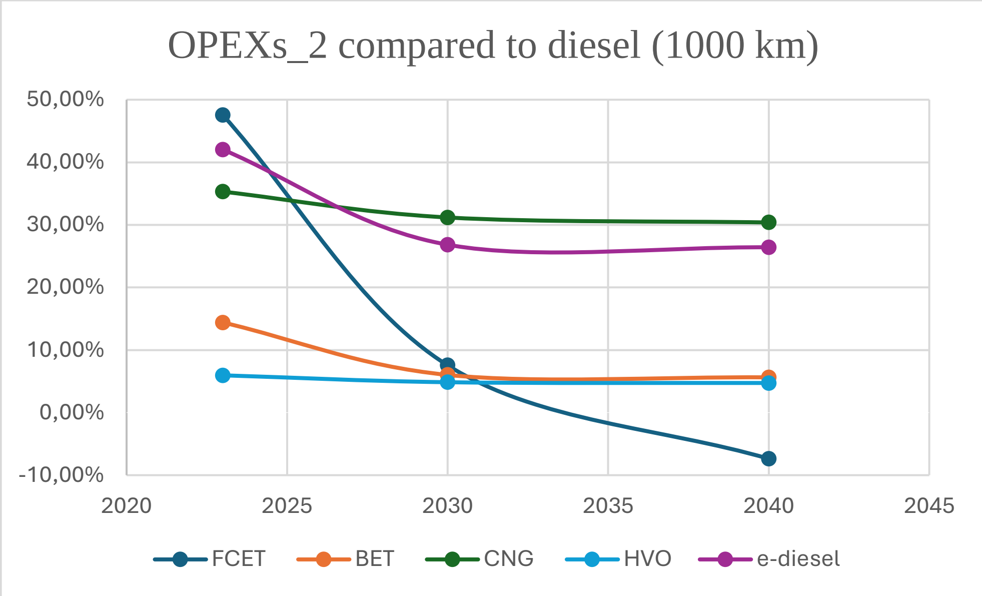

Figure 16. FCET, BET, CNG, HVO and e-diesel trucks OPEXs_1 compared to that of diesel trucks with a 1,000 km daily driving range for 2023, 2030 and 2040.

Analysing the 2023-year, e-diesel trucks have the highest OPEX_1 followed by FCETs. However, for OPEX_2 this order is inverted. The next positions on the ranking are held by CNG, battery electric and HVO trucks respectively for OPEX_1 as well as for OPEX_2. Finally, the lowest OPEX in both cases corresponds to diesel trucks as opposed to what happened for the same year for trucks with 500 km and 800 km daily driving ranges, in which battery electric trucks had the lowest OPEX. As it can be observed, applying the CO_2 road fees do not make any difference in the ranking for BETs, but it is relevant for FCETs, as when applying these CO_2 charges they are placed on the OPEX ranking below the e-diesel technology rather than on top.

As it occurred for trucks with 500 km and 800 km daily driving ranges, for years 2030 and 2040 the OPEX ranking will vary mainly due to changes in the estimated fuel consumption, the fuel and energy prices and the operation and maintenance costs of the different technologies.

Focussing on year 2030, the highest OPEX_1 and OPEX_2 correspond to CNG trucks, being closely followed by e-diesel trucks in both cases. The next positions are occupied by HVO, diesel and fuel-cell trucks respectively for OPEX_1, whereas for OPEX_2 they are held by fuel-cell, battery electric and HVO trucks in this order. Finally, BETs have the lowest OPEX_1 (CO_2 road charges being applied) while the lowest OPEX_2 corresponds to diesel trucks (CO_2 fees not being considered).

Moreover, for 2030 FCETs and BETs have an OPEX_1 that is 1.2 % and 2.6 % lower than that of diesel trucks, while their OPEX_2 is 7.6 % and 6 % higher than that of diesel trucks as it can be observed in *Figures 15 and 16*. All of this implies that for this year and daily driving range CO_2 road charges do have a significant impact on the OPEX rankings as the position of FCETs and BETs is favoured when they are applied. It is remarkable that whereas for the previously studied daily driving ranges BETs have both, the lowest OPEX_1 and OPEX_2, for trucks with a 1,000 km daily driving range the lowest OPEX_2 matches with diesel trucks.

Moving on to year 2040, the highest OPEX_1 and OPEX_2 corresponds to CNG trucks, closely followed by e-diesel ones. The next positions on the ranking for OPEX_1 are held by HVO, diesel and battery electric trucks in this order, whereas for OPEX_2 they are held by battery electric, HVO and diesel trucks respectively. In contrast to what happened for trucks with 500 km and 800 km daily driving ranges, fuel cell trucks are the ones with the lowest OPEX in both scenarios for trucks with a 1,000 km daily driving range whether the CO_2 is applied or not. While for OPEX_1 that of FCETs and BETs is 14.7 % and 2.7% lower than that of diesel trucks, only OPEX_2 of FCETs is lower than that of diesel trucks (by 7.4 %) as OPEX_2 for BETs is 5.6 % higher (*Figures 15 and 16*).

It is needed to acknowledge that for trucks with a 1,000 km daily driving range BETs have not always the lowest OPEX_1 and OPEX_2 during the 2023-2040 period opposed to what occurred with the previously studied driving ranges (it only happens for OPEX_1 in 2030). On the contrary, for this daily driving range it can be observed that diesel trucks are the ones with the lowest OPEX_1 and OPEX_2 for 2023 and with the lowest OPEX_2 for 2030. Additionally, for year 2040 the lowest OPEX matches with fuel cell trucks in both scenarios, which is something that has not happened in any other daily driving range.

For trucks with a daily driving range of 1,000 km it can be seen that the CO_2 road fees have a higher impact for 2030 as by applying them BETs have the lowest OPEX followed by FCETs (otherwise the lowest OPEXs would correspond to diesel and HVO trucks in this order). For 2040, this European measure influences the position of BETs in the OPEX ranking, but it does not modify that of FCETs, which would be the trucks with the lowest OPEX whether the measure is applied or not if the estimates made by the experts are accurate.

According to the predictions made for 2040, for all driving ranges it can be observed that CNG and e-diesel trucks will not be competitive in terms of OPEX with the other analysed technologies in the long term. Moreover, while for smaller driving ranges battery electric trucks have been estimated to be the ones with the lowest OPEX, for 1,000 daily driving range trucks fuel cell trucks have been predicted to be the most competitive ones in this field followed by BETs or diesel trucks, depending on if the CO_2 fees are being applied or not.

4.1.3. TCO RESULTS

4.1.3.1. TCO RESULTS (500 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 500 km *Tables 143, 144 and 145* show the results for the TCO for years 2023, 2030 and 2040.

OPEX_1 corresponds to the trucks' OPEX considering the CO_2 road fees that the European Parliament has already approved and are supposed to be applied in the different European member states from 2023 onwards. OPEX_2 refers to the trucks OPEX without applying such CO_2 road fees as there are member states which are postponing this measure.

Due to this two TCOs have been computed: TCO_1, in which OPEX_1 is used and TCO_2, in which OPEX_2 has been considered for the calculations.

In the following *Tables* referring to TCO, "SUB" refers to subsidies, "SV" to scrappage value, "CRF" to capital recovery factor, "i" to discount rate, "N" to lifetime of the vehicle and "AKT" to annual kilometres travelled.

TCO for each technology (500 km driving range) (€/km)											
	2023										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	454.920	20.000	106.000	0,26	9,5%	5	190.601	190.601	119.259	2,03	2,03
BET	358.453	20.000	76.000	0,26	9,5%	5	119.993	119.993	119.259	1,41	1,41
CNG	149.611	20.000	47.000	0,26	9,5%	5	183.988	174.447	119.259	1,40	1,34
HVO	137.243	-	42.000	0,26	9,5%	5	151.560	142.019	119.259	1,22	1,16
e-diesel	137.243	-	42.000	0,26	9,5%	5	193.664	184.123	119.259	1,49	1,43
Diesel	137.243	-	42.000	0,26	9,5%	5	146.434	136.893	119.259	1,18	1,12

Table 143. TCO for trucks with a 500 km daily driving range based on their technology in €/km for year 2023.

TCO for each technology (500 km driving range) (€/km)											
	2030										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	222.114	20.000	62.000	0,26	9,5%	5	139.307	139.307	119.259	1,25	1,25
BET	182.176	20.000	53.000	0,26	9,5%	5	110.551	110.551	119.259	0,99	0,99
CNG	165.736	20.000	46.000	0,26	9,5%	5	169.445	159.904	119.259	1,35	1,28
HVO	157.479	-	43.000	0,26	9,5%	5	142.616	133.075	119.259	1,20	1,14
e-diesel	157.479	-	43.000	0,26	9,5%	5	166.411	156.870	119.259	1,36	1,29
Diesel	157.479	-	43.000	0,26	9,5%	5	138.742	129.202	119.259	1,18	1,12

Table 144. TCO for trucks with a 500 km daily driving range based on their technology in €/km for year 2030.

TCO for each technology (500 km driving range) (€/km)											
	2040										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	219.922	20.000	58.000	0,26	9,5%	5	127.404	127.404	119.259	1,18	1,18
BET	189.700	20.000	47.000	0,26	9,5%	5	114.964	114.964	119.259	1,05	1,05
CNG	202.401	20.000	46.000	0,26	9,5%	5	174.095	164.554	119.259	1,46	1,39
HVO	193.184	-	43.000	0,26	9,5%	5	147.279	137.738	119.259	1,31	1,25
e-diesel	193.184	-	43.000	0,26	9,5%	5	171.350	161.809	119.259	1,47	1,40
Diesel	193.184	-	43.000	0,26	9,5%	5	143.405	133.864	119.259	1,29	1,22

Table 145. TCO for trucks with a 500 km daily driving range based on their technology in €/km for year 2040.

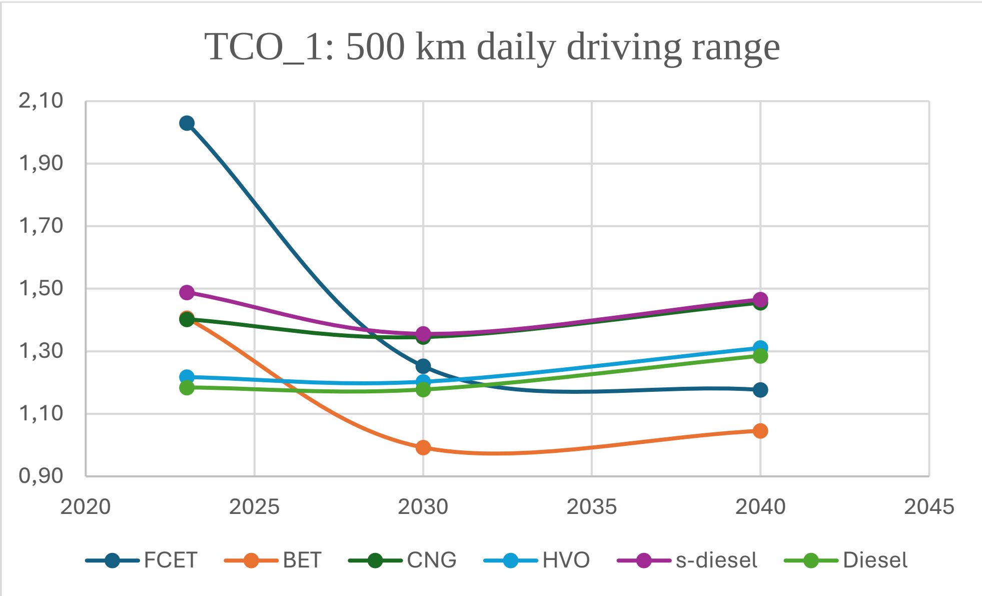

Figure 17. TCO_1 (€/km) for trucks with a 500 km daily driving range based on their technology for years 2023, 2030 and 2040.

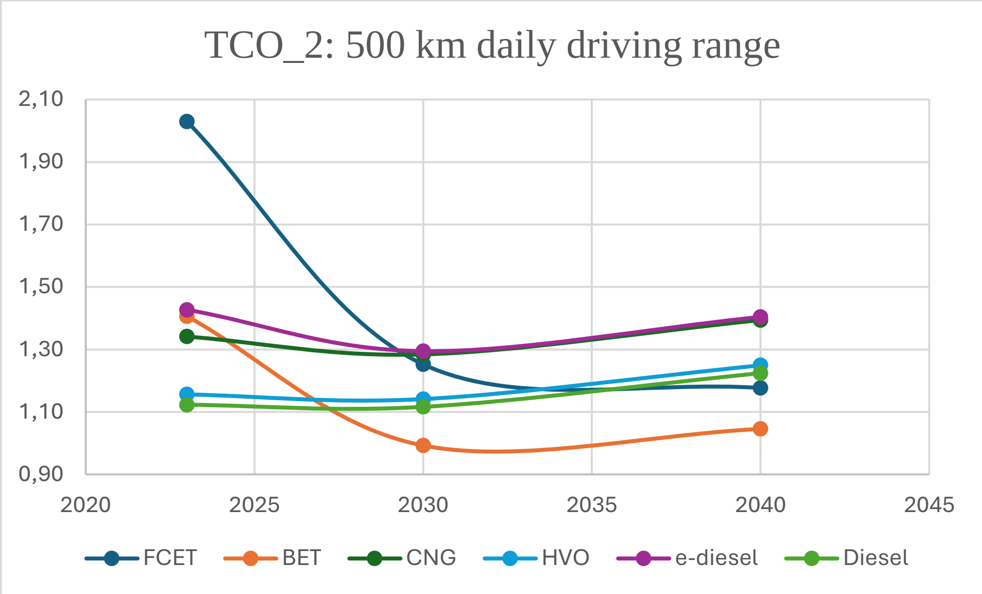

Figure 18. TCO_2 (€/km) for trucks with a 500 km daily driving range based on their technology for years 2023, 2030 and 2040.

Focusing on the year 2023, as it can be observed in *Table 143* the fuel cell is the technology with the highest TCO_1 and TCO_2, followed by e-diesel trucks (there is around a 26.7% difference when the CO_2 fees are applied and approximately a 29.7 % difference between these two technologies when this measure is not considered). Next on both rankings are battery electric, CNG and HVO trucks in this order. When taking into account the CO_2 road charges, BETs and CNG trucks' TCOs are really similar (there is less than a 0.3 % variation), yet when not considering this European directive the difference increases up to around 4.6 %). Finally, the lowest TCO_1 and TCO_2 for 2023 correspond to diesel trucks, whose TCO_1 is around 15.8 % lower than that of BETs and whose TCO_2 is approximately 25.2 % lower compared to BETs.

Analysing year 2030, which is displayed in *Table 144*, the ranking is the same for TCO_1 and TCO_2, with e-diesel trucks having the highest TCO closely followed by CNG trucks (there is less than a 0.8 % variation between both technologies). The next positions are held by fuel cell, HVO and diesel trucks in this order, being around 4 % and 8.9 % the difference between FCETs and HVO trucks for TCO_1 and TCO_2 respectively. The differences between HVO and diesel trucks are even smaller, (around a 2.1 % in both scenarios). Finally, for 2030 the lowest TCOs correspond to BETs, whose TCO_1 and TCO_2 are around 15.7 % and 12.5 % lower respectively compared to those of diesel trucks.

Talking about year 2040, *Table 145* shows that e-diesel trucks have the highest TCO_1 and TCO_2, being closely followed by CNG trucks (there is around a 0.7 % difference between these technologies in both cases). The next positions on both rankings are occupied by HVO, diesel and fuel cell trucks in this order. The difference between HVO and diesel trucks' TCOs is of around 2 % for both scenarios. When it comes to diesel and fuel-cell technologies the difference is of around 8.5 % for TCO_1 (CO_2 charges considered) and of around 3.9 % for TCO_2 (CO_2 charges not applied). Lastly, the lowest TCO matches with BETs in both cases. The difference in TCO between FCETs and BETs is of around 11.1 % in both scenarios. However, the TCO variation between BETs and diesel trucks is of around 18.7 % and 14.6 % for TCO_1 and TCO_2 respectively.

Studying the 2023-2040 period for trucks with a 500 km daily driving range, it can be observed in *Figures 17 and 18* that whereas for 2023 zero-emission trucks have high TCOs compared to other technologies such as diesel (which is the one with the lowest TCOs for this year), for years 2030 and 2040 BETs and FCETs become more competitive. For 2030 and 2040 BETs are the technology with the lowest TCO and in 2030 FCETs are surpassed by e-diesel and CNG trucks. The position of fuel cell trucks improves even more for 2040, year in which they obtain the second lowest TCO in both rankings.

Moreover, it is needed to mention that for 2030 and 2040 e-diesel and CNG trucks are the ones with the highest TCOs (*Figures 17 and 18*), which implies that these technologies will not be competitive anymore in the long term if predictions from the experts are accurate. Additionally, despite diesel trucks being the most competitive ones for 2023, they would have higher TCOs than those of BETs for 2030 and than those of BETs and FCETs for 2040 if estimates are accomplished. This shows that probably in the long term most of the 500 km daily driving range trucks' freight will be composed of battery electric, fuel-cell and diesel trucks as they would be the most competitive technologies if predictions are true.

4.1.3.2. TCO RESULTS (800 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 800 km *Tables 146, 147 and 148* show the results for the TCO for years 2023, 2030 and 2040.

TCO for each technology (800 km driving range) (€/km)											
	2023										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	502.802	20.000	125.000	0,26	9,5%	5	245.473	245.473	158.349	1,85	1,85
BET	486.920	20.000	72.000	0,26	9,5%	5	145.667	145.667	158.349	1,40	1,40
CNG	154.184	20.000	55.000	0,26	9,5%	5	231.399	218.731	158.349	1,29	1,22
HVO	138.288	-	48.000	0,26	9,5%	5	187.810	175.142	158.349	1,09	1,03
e-diesel	138.288	-	48.000	0,26	9,5%	5	243.715	231.047	158.349	1,36	1,30
Diesel	138.288	-	48.000	0,26	9,5%	5	181.004	168.336	158.349	1,06	0,99

Table 146. TCO for trucks with an 800 km daily driving range based on their technology in €/km for year 2023.

TCO for each technology (800 km driving range) (€/km)											
	2030										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	242.927	20.000	75.000	0,26	9,5%	5	170.063	170.063	158.349	1,11	1,11
BET	229.862	20.000	71.000	0,26	9,5%	5	130.196	130.196	158.349	0,90	0,90
CNG	172.882	20.000	55.000	0,26	9,5%	5	211.599	198.931	158.349	1,22	1,16
HVO	158.720	-	49.000	0,26	9,5%	5	175.051	162.383	158.349	1,06	1,00
e-diesel	158.720	-	49.000	0,26	9,5%	5	206.645	193.977	158.349	1,21	1,15
Diesel	158.720	-	49.000	0,26	9,5%	5	169.908	157.240	158.349	1,03	0,97

Table 147. TCO for trucks with an 800 km daily driving range based on their technology in €/km for year 2030.

TCO for each technology (800 km driving range) (€/km)											
	2040										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	235.878	20.000	71.000	0,26	9,5%	5	152.449	152.449	158.349	1,02	1,02
BET	228.574	20.000	66.000	0,26	9,5%	5	134.430	134.430	158.349	0,93	0,93
CNG	210.740	20.000	55.000	0,26	9,5%	5	216.239	203.572	158.349	1,30	1,24
HVO	194.772	-	49.000	0,26	9,5%	5	179.713	167.045	158.349	1,14	1,08
e-diesel	194.772	-	49.000	0,26	9,5%	5	211.675	199.007	158.349	1,30	1,23
Diesel	194.772	-	49.000	0,26	9,5%	5	174.570	161.902	158.349	1,12	1,05

Table 148. TCO for trucks with an 800 km daily driving range based on their technology in €/km for year 2040.

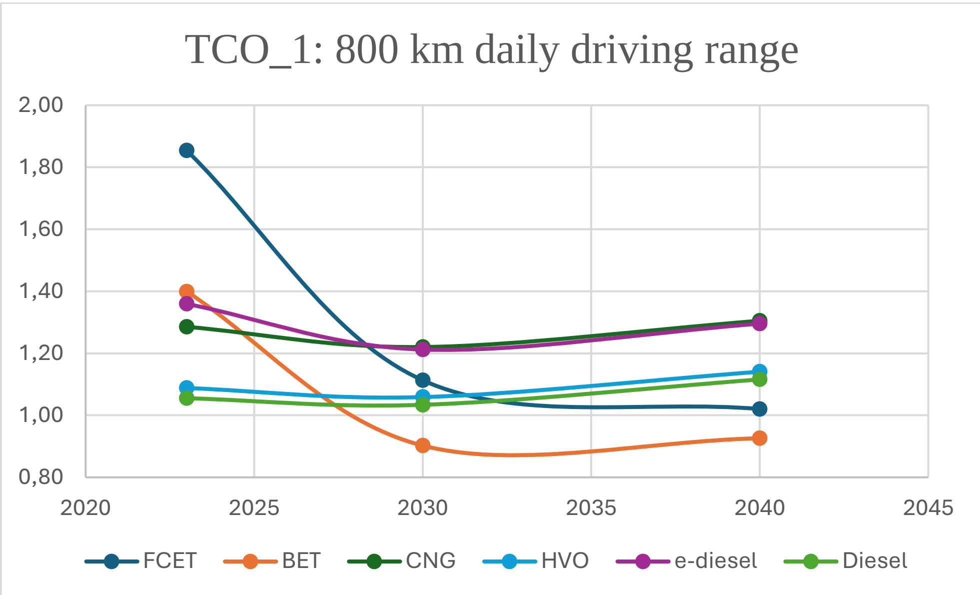

Figure 19. TCO_1 (€/km) for trucks with an 800 km daily driving range based on their technology for years 2023, 2030 and 2040.

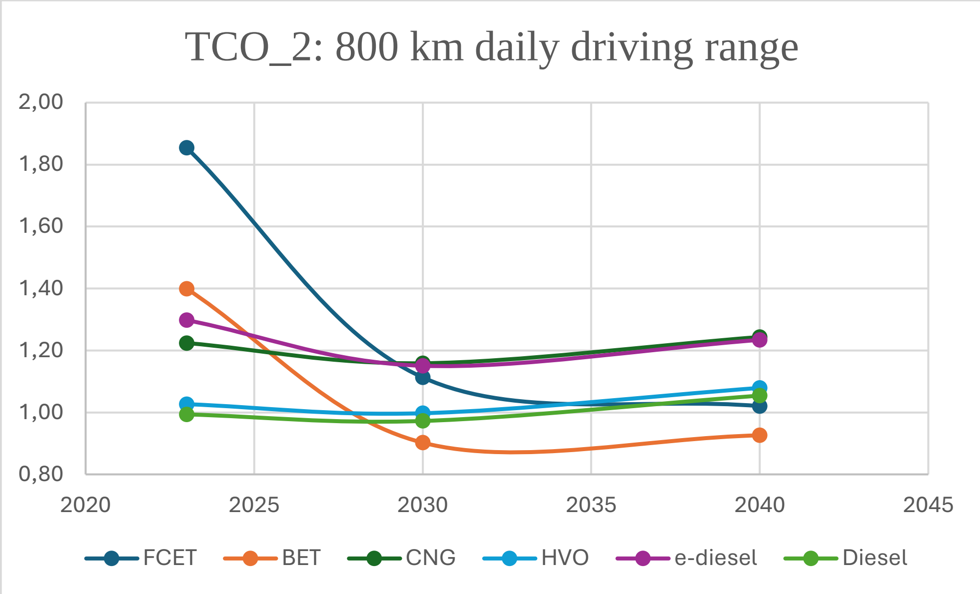

Figure 20. TCO_2 (€/km) for trucks with an 800 km daily driving range based on their technology for years 2023, 2030 and 2040.

As it can be observed in *Table 146*, for year 2023 fuel-cell trucks are the ones with the highest TCO, followed by BETs, whose TCO is around 24.5 % lower. The next positions on both rankings are held by e-diesel, CNG and HVO trucks in this order. Finally, the lowest TCOs for 2023 correspond to diesel trucks -approximately 43.1 % and 24.6 % lower than that of FCETs and BETs in terms of TCO_1 and around 46.4 % and 29 % lower than that of FCETs and BETs in terms of TCO_2-. Moreover, for trucks with 500 km and 800 km daily driving ranges, FCETs have the highest TCOs whereas diesel trucks have the lowest ones for 2023.

When it comes to year 2030, whose data can be observed in *Table 147*, the ranking is the same for TCO_1 and TCO_2 with CNG trucks having the highest TCOs closely followed by e-diesel trucks (there is around a 0.7 % difference between both technologies). The next positions are held by fuel cell, HVO and diesel trucks in this order in both rankings, being around 4.9 % and 10.4 % the difference between FCETs and HVO trucks for TCO_1 and TCO_2 respectively. The variations between HVO and diesel trucks are smaller, being of around 2.5 % in both scenarios. Finally, for 2030 the lowest TCOs correspond to BETs, whose TCO_1 and TCO_2 are around 12.7 % and 7.2 % lower respectively compared to those of diesel trucks.

By analysing year 2040, which is displayed in *Table 148*, it can be observed that CNG trucks have the highest TCO_1 and TCO_2 being closely followed by e-diesel trucks (there is around a 0.7 % difference in both cases). The next positions on both rankings correspond to HVO, diesel and fuel cell trucks in this order. The difference between HVO and diesel trucks' TCOs is of approximately 2.2 % in both scenarios. Talking about diesel and fuel cell technologies the difference between them is of around 8.6 % for TCO_1 (CO_2 charges applied) and of around 3.2 % for TCO_2 (CO_2 charges not considered).

Finally, the lowest TCO matches with BETs in both cases. The difference in TCO between FCETs and BETs is of around 9.2 %. On the contrary, the TCO variation between BETs and diesel trucks is of around 17 % and 12.2 % for TCO_1 and TCO_2 respectively.

Studying the 2023-2040 period, for trucks with an 800 km daily driving range it can be observed in *Figures 19 and 20* that despite zero-emission trucks having the highest TCOs for year 2023, for year 2030 and 2040 BETs have the lowest TCOs. Moreover, during this period the position of FCETs on the ranking improves, achieving its best record for year 2040, in which FCETs' TCO occupies the second lowest position on both rankings. All of this implies that for the following decades zero-emission trucks will become more competitive, especially battery electric ones, as it occurred with trucks with a 500 km daily driving range.

Furthermore, it is noticeable that for 2030 and 2040, as it happened for daily driving ranges of 500 km, e-diesel and CNG trucks are the ones with the highest TCOs, which implies that if estimates from scientists for the next decades are correct, these technologies will not be competitive anymore (*Figures 19 and 20*). Moreover, yet diesel trucks are the most competitive ones for 2023, they would have higher TCOs than those of BETs for 2030 and than those of BETs and FCETs for 2040 if predictions are accurate. Based on this, it could be reasonable to deduce that probably in the long term most of the 800 km daily driving range trucks' freight will be composed of battery electric, fuel-cell and diesel trucks as they would be the most competitive technologies. As it can be observed, this is the same conclusion that was previously obtained for trucks with a 500 km daily driving range.

4.1.3.3. TCO RESULTS (1,000 KM DAILY DRIVING RANGE)

For trucks with a daily driving range of 1,000 km *Tables 149, 150 and 151* show the results for the TCO for years 2023, 2030 and 2040.

TCO for each technology (1000 km driving range) (€/km)											
	2023										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	525.033	20.000	98.000	0,26	9,5%	5	290.922	290.922	201.444	1,68	1,68
BET	561.503	20.000	64.000	0,26	9,5%	5	225.571	225.571	201.444	1,51	1,51
CNG	154.184	20.000	55.000	0,26	9,5%	5	282.906	266.790	201.444	1,21	1,15
HVO	138.984	-	48.000	0,26	9,5%	5	225.040	208.924	201.444	1,00	0,94
e-diesel	138.984	-	48.000	0,26	9,5%	5	296.160	280.044	201.444	1,27	1,21
Diesel	138.984	-	48.000	0,26	9,5%	5	213.290	197.174	201.444	0,95	0,89

Table 149. TCO for trucks with a 1,000 km daily driving range based on their technology in €/km for year 2023.

TCO for each technology (1000 km driving range) (€/km)											
	2030										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	254.821	20.000	79.000	0,26	9,5%	5	196.707	196.707	201.444	0,99	0,99
BET	263.694	20.000	81.000	0,26	9,5%	5	193.908	193.908	201.444	0,99	0,99
CNG	173.541	20.000	55.000	0,26	9,5%	5	256.034	239.918	201.444	1,13	1,07
HVO	159.547	-	49.000	0,26	9,5%	5	207.885	191.770	201.444	0,96	0,90
e-diesel	159.547	-	49.000	0,26	9,5%	5	248.077	231.962	201.444	1,11	1,05
Diesel	159.547	-	49.000	0,26	9,5%	5	199.006	182.890	201.444	0,92	0,86

Table 150. TCO for trucks with a 1,000 km daily driving range based on their technology in €/km for year 2030.

TCO for each technology (1000 km driving range) (€/km)											
	2040										
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
FCET	246.516	20.000	74.000	0,26	9,5%	5	173.726	173.726	201.444	0,89	0,89
BET	256.154	20.000	76.000	0,26	9,5%	5	198.120	198.120	201.444	1,00	1,00
CNG	211.510	20.000	55.000	0,26	9,5%	5	260.653	244.538	201.444	1,20	1,13
HVO	195.832	-	49.000	0,26	9,5%	5	212.548	196.432	201.444	1,02	0,96
e-diesel	195.832	-	49.000	0,26	9,5%	5	253.207	237.092	201.444	1,18	1,12
Diesel	195.832	-	49.000	0,26	9,5%	5	203.668	187.553	201.444	0,99	0,93

Table 151. TCO for trucks with a 1,000 km daily driving range based on their technology in €/km for year 2040.

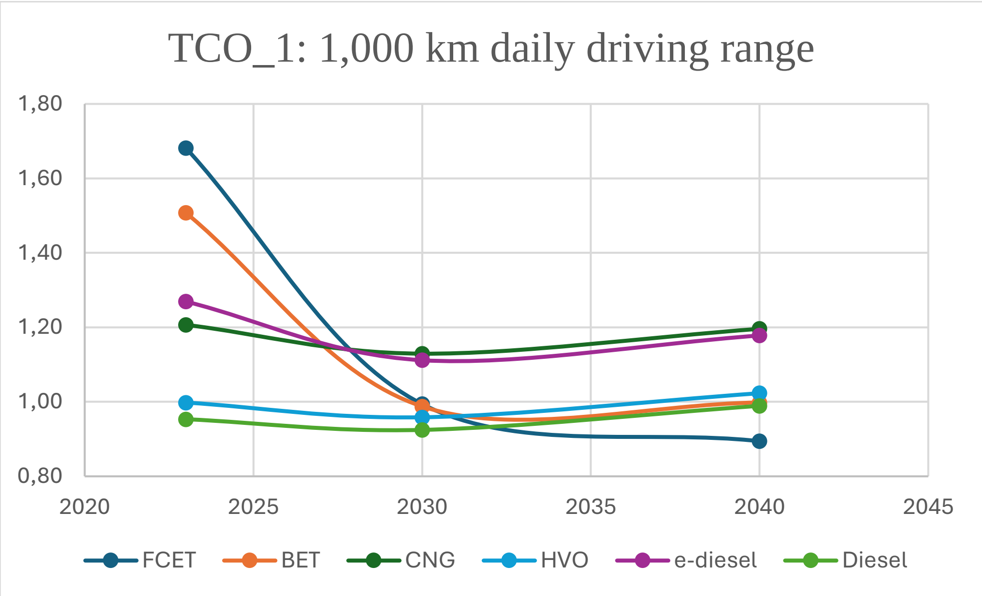

Figure 21. TCO_1 (€/km) for trucks with a 1,000 km daily driving range based on their technology for years 2023, 2030 and 2040.

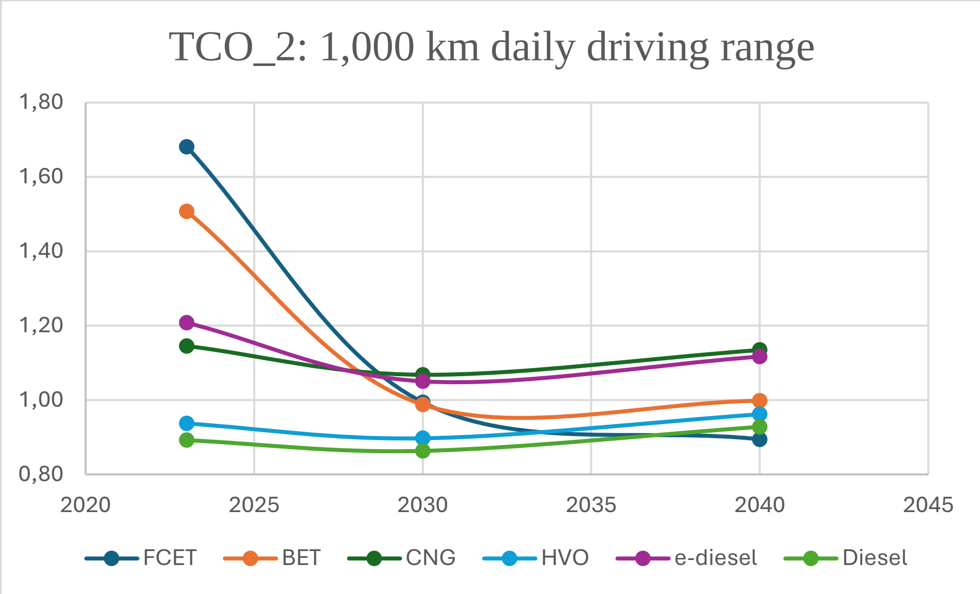

Figure 22. TCO_2 (€/km) for trucks with a 1,000 km daily driving range based on their technology for years 2023, 2030 and 2040.

For year 2023 *Table 149* shows the computed TCOs for each technology, being fuel-cell trucks the ones with the highest TCO_1 and TCO_2, followed by BETs (there is approximately a 10.4 % TCO difference between these two technologies in both cases). The next positions on both rankings correspond to e-diesel, CNG and HVO trucks in this order. Finally, the lowest TCO_1 and TCO_2 for 2023 correspond to diesel trucks, whose TCO_1 is approximately 43.3 % lower than that of FCETs and 36.8 % lower than that of BETs and whose TCO_2 is approximately 47 % lower compared to FCETs and around 40.8 % lower compared to BETs. Analysing TCOs across daily driving ranges, for trucks with 500 km and 800 km as well as 1,000 km daily driving ranges, FCETs have the highest TCOs while diesel trucks have the lowest ones for 2023. In contrast, when it comes to BETs, their TCO is lower than those of e-diesel trucks for 500 km daily driving ranges while for 800 km and 1,000 km daily driving ranges e-diesel trucks' TCOs are below those for BETs.

Focusing on year 2030, for which the computed TCOs can be observed in *Table 150*, the ranking is the same for TCO_1 and TCO_2. The highest TCOs are for CNG trucks, being closely followed by e-diesel trucks (the differences in TCOs between these technologies are of around 1.6 % in both scenarios). The next positions are held by fuel cell, battery electric and HVO trucks in this order in both rankings, being around 0.6 % the TCO difference between FCETs and BETs. The variations between BETs and HVO trucks are of approximately 3 % for TCO_1 and of around 9.2 % for TCO_2. Finally, for 2030 the lowest TCOs correspond to diesel trucks, whose TCO_1 and TCO_2 are around 3.5 % and 3.8 % lower respectively compared to those of HVO trucks and around 6.4 % and 12.6 % lower respectively compared to those of BETs.

Talking about year 2040, which is displayed in *Table 151*, CNG trucks have the highest TCO_1 and TCO_2 being closely followed by e-diesel trucks (there is around a 1.5 % difference in TCO between these technologies in both cases). For TCO_1, the next positions of the ranking are occupied by HVO, battery electric and diesel trucks in this order while for TCO_2 the next positions correspond to battery electric, HVO and diesel trucks. As it can be observed, for 2040 CO_2 road charges do have an impact on trucks with a 1,000 km daily driving range as they make BETs more competitive than HVO trucks, which is something that do not occur for the other driving ranges studied for this year.

The TCOs from HVO and battery electric trucks are close, being 2.4 % and 3.6 % the TCO variations between these technologies for TCO_1 and TCO_2 respectively. Diesel is the technology with the second lowest TCO whether CO_2 fees are considered or not. For TCO_1, the TCO differences between diesel and battery electric as well as diesel and HVO trucks are of around 0.9 % and 3.3 % respectively. However, for TCO_2 those TCO differences are of 7 % and 3.5 % when comparing diesel to battery electric and HVO trucks respectively. Finally, the lowest TCO in both scenarios corresponds to FCETs, whose TCO is around 9.6 % and 3.6 % lower than that of diesel trucks' TCO_1 and TCO_2 respectively.

Studying the 2023-2040 period, for trucks with a 1,000 km daily driving range it can be observed in *Figures 21 and 22* that while zero-emission trucks have the highest TCOs for year 2023, they become more competitive for the following decades, especially FCETs, which begin by having the highest TCO and finish by having the lowest one in 2040. This progression only occurs for trucks with a 1,000 km daily driving range as for those with 500 km and 800 km daily driving ranges the lowest TCO for 2030 onwards corresponds to BETs.

However, for trucks with 1,000 km daily driving range BETs are not especially competitive, as diesel and HVO trucks have lower TCOs for 2030 and the diesel's TCOs are lower for 2040 in both scenarios too. Consequently, whereas for 2030 HVO and diesel are the most competitive technologies, for 2040 fuel cell trucks are the most competitive ones followed by diesel trucks and BETs or HVO trucks depending on if CO_2 road charges are applied or not. This do not match with the tendency that trucks with 500 km and 800 km daily driving ranges follow, in which BETs are the most competitive technology from 2030 onwards.

Furthermore, it is noticeable that despite not following the tendency when it comes to zero-emissions technologies, talking about e-diesel and CNG trucks predictions for all driving ranges are shared: these technologies will not be competitive anymore from 2030 onwards as they are the ones with the highest TCOs (*Figures 21 and 22*).

Based on this and considering the analysis made in the previous paragraphs, it can be deduced that in the long term it is likely that most of the 1,000 km daily driving range trucks' freight is composed by fuel-cell and diesel trucks mainly, followed by BETs or

HVO trucks depending on the imposed fees. This conclusion differs from the ones made for trucks with 500 km and 800 km daily driving ranges.

4.2. CASE 1 RESULTS: PRICE VARIATIONS IN THE BET BATTERY

According to paper [7], near market sources expect the retail unitary prices of batteries to decrease to 94 €2020/kWh on average for 2040, being the lowest estimated battery retail price of 87.9 €2020/kWh.

Considering the annual Spanish inflation rate between 2020 and 2023 (1 €2020 equals 1,157 €2023) the estimates for 2040 are of 108.76 €/kWh on average and of 101.70 €/kWh for the most favourable scenario, which are both lower retail prices than the one selected for the base case. [57]

For being as optimistic as possible, in *Case 1* the selected unitary retail battery price will be the lowest estimation from source [9], which is 101.70 €/kWh for 2040. This selected value implies a 14.45 % decrease in the unitary retail price compared to the base case.

For *Case 1* it will be assumed that the retail battery price for year 2023 is the same as in the *Base Case*. However, for 2030 the price will be 55 % lower than that of 2023, which matches the optimistic predictions for this year. [8], [9]

Tables 152 and 153 show the unitary retail price of the BET's battery in €/kWh and the total retail price of the BET battery in € for 2023, 2030 and 2040 respectively. The battery sizes for the different years are the ones selected for the *Base Case*.

Unitary retail price for the BET battery (€/kWh)			
	2023	2030	2040
Near market	304,4	137,0	101,7

Table 152. Selected unitary retail prices of the energy battery of BETs in €/kWh for years 2023, 2030 and 2040 for Case 1. [7], [8], [9], [57]

Total retail price of the BET battery (€)			
	2023	2030	2040
5-LH (500 km)	239.885,32	73.289,84	54.409,66
5-LH (800 km)	368.351,83	118.085,68	87.665,66
5-LH (1000 km)	442.935,47	149.867,44	111.260,13

Table 153. Total unitary retail prices of the energy battery of BETs in €/kWh for years 2023, 2030 and 2040 for Case 1. [4], [5], [7], [8], [9], [35], [57]

4.2.1. CAPEX RESULTS

Table 154 shows the CAPEX of battery electric trucks with a 500 km daily driving range for years 2023, 2030 and 2040 for *Case 1*. Moreover, *Figure 23* illustrates the comparison between the *Base Case* and *Case 1* in terms of CAPEX.

CAPEX considering the changing parameter (500 km driving range) (€)				
	Powertrain	Energy storage	Rest of the truck	CAPEX
	2023			
BET	39.578,00	239.885,32	78.989,74	358.453,06
	2030			
BET	21.248,90	73.289,84	82.908,87	177.447,61
	2040			
BET	23.610,62	54.409,66	102.489,27	180.509,55

Table 154. CAPEX for Case 1 BETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

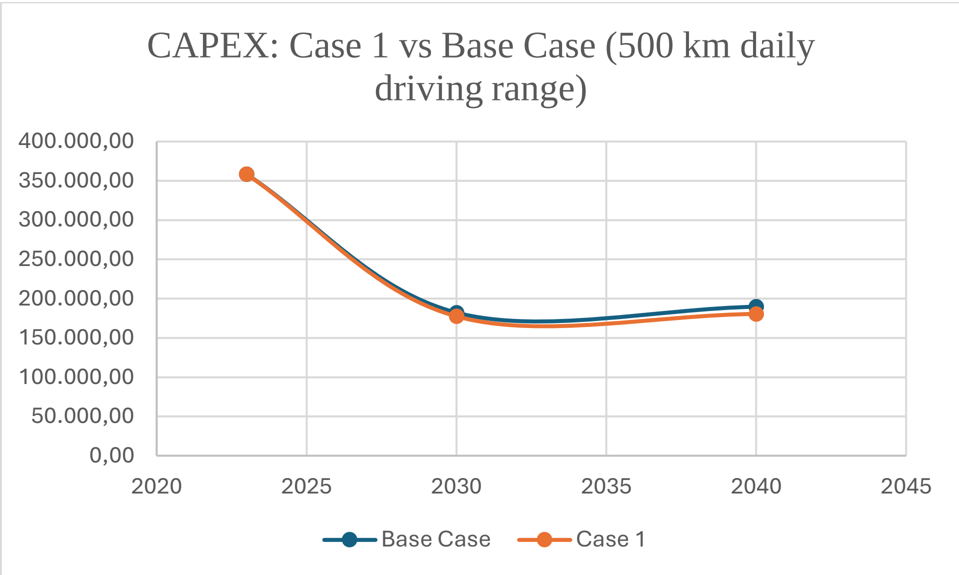

Figure 23. Comparison between the Base Case and Case 1 in terms of CAPEX for BETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 154*, for *Case 1* the CAPEX for BETs with a 500 km daily driving range is estimated to be modified from €358,453.06 in 2023 to €177,447.61 for 2030 and to €180,509.55 for 2040. For 2030 and 2040 these estimates are slightly below the values obtained in the *Base Case* as it is shown in *Figure 23*. When comparing the two cases in terms of CAPEX, the CAPEX of *Case 1* is around 2.6 % and 4.8 % lower than that of the *Base Case* for 2030 and 2040 respectively.

For battery electric trucks with an 800 km daily driving range, *Table 155* shows their CAPEX for years 2023, 2030 and 2040 for *Case 1*. In addition to this, in *Figure 24* the comparison between the *Base Case* and *Case 1* in terms of CAPEX is displayed.

CAPEX considering the changing parameter (800 km driving range) (€)				
	Powertrain	Energy storage	Rest of the truck	CAPEX
	2023			
BET	39.578,00	368.351,83	78.989,74	486.919,57
	2030			
BET	21.248,90	118.085,68	82.908,87	222.243,46
	2040			
BET	23.610,62	87.665,66	102.489,27	213.765,55

Table 155. CAPEX for Case 1 BETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

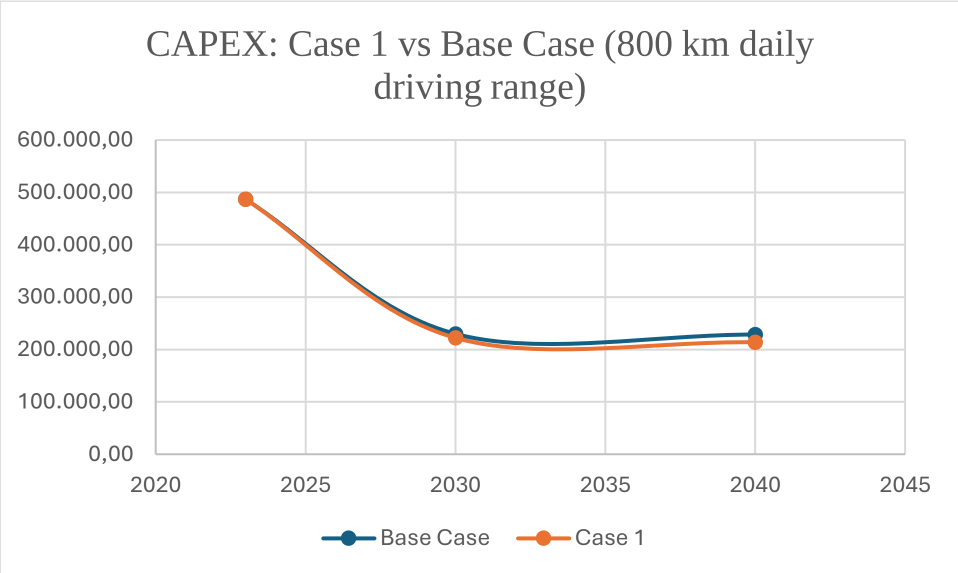

Figure 24. Comparison between the Base Case and Case 1 in terms of CAPEX for BETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 155*, for *Case 1* the CAPEX for BETs with an 800 km daily driving range is estimated to decrease from €486,919.57 in 2023 to €222,243.46 for 2030 and to €213,765.55 for 2040. These predictions are below the values obtained in the *Base Case* as it can be seen on *Figure 24* for 2030 and 2040. When comparing the two cases in terms of CAPEX for 800 km daily driving range trucks, the CAPEX of *Case 1* is around 3.3 % and 6.5 % lower than that of the *Base Case* for 2030 and 2040 respectively, which is slightly more than the decrement obtained for trucks with a daily driving range of 500 km.

When it comes to BETs with a 1,000 km daily driving range, *Table 156* shows their CAPEX for years 2023, 2030 and 2040 for *Case 1*. Furthermore, *Figure 25* illustrates the comparison between the *Base Case* and *Case 1* in terms of CAPEX for trucks with the previously mentioned daily driving range.

CAPEX considering the changing parameter (1000 km driving range) (€)				
	Powertrain	Energy storage	Rest of the truck	CAPEX
	2023			
BET	39.578,00	442.935,47	78.989,74	561.503,20
	2030			
BET	21.248,90	149.867,44	82.908,87	254.025,22
	2040			
BET	23.610,62	111.260,13	102.489,27	237.360,02

Table 156. CAPEX for Case 1 BETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

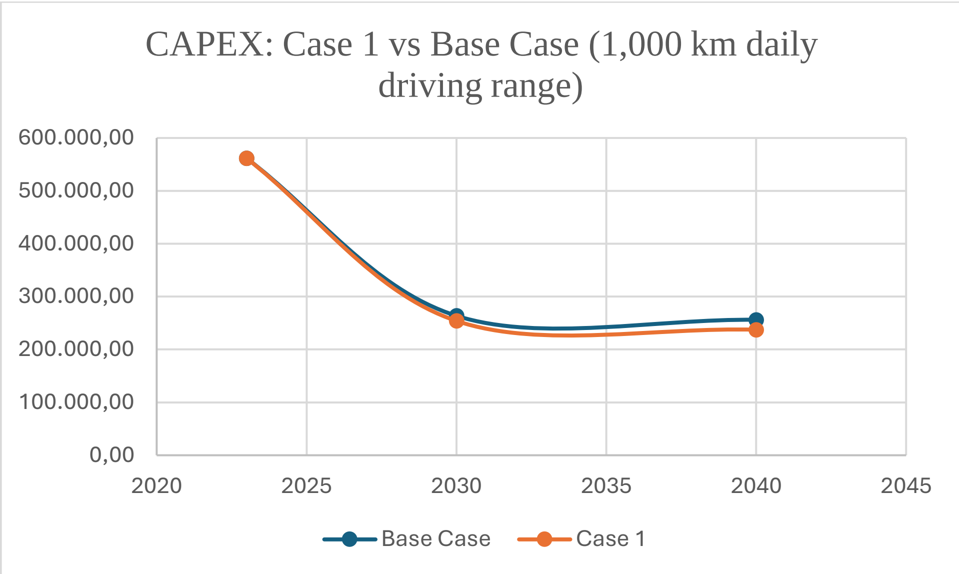

Figure 25. Comparison between the Base Case and Case 1 in terms of CAPEX for BETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

As it can be seen in *Table 156*, for *Case 1* the CAPEX for BETs with a 1,000 km daily driving range is estimated to decrease from €561,503.20 in 2023 to €254,025.22 for 2030 and to €237,360.02 for 2040. Compared to the values obtained in the *Base Case*, for 2030 and 2040 these estimates are lower as it can be seen in *Figure 25*. Analysing both cases in terms of CAPEX for 1,000 km daily driving range trucks, the CAPEX of *Case 1* is approximately 3.7 % and 7.3 % lower than that of the *Base Case* for 2030 and 2040 respectively, which is slightly higher than the decrements obtained for trucks with 500 km and 800 km daily driving ranges.

4.2.2. OPEX RESULTS

For *Case 1* the OPEX stays the same as in the *Base Case*.

4.2.3. TCO RESULTS

In the *Base Case* there were two OPEXs (OPEX_1 and OPEX_2) as in one of them the CO_2 road charges already approved by the European Parliament that should be implemented by the EU member states from 2023 onwards are considered but in the other one they are not. As BETs are considered a zero-emission technology and as a result are exempted from these charges, both OPEXs as well as TCOs are the same and consequently have been unified in OPEX 1 & 2 and TCO 1 & 2 as it can be observed on Tables X1, X2 and X3.

Focusing on trucks with a 500 km daily driving range, *Table X1* shows the TCO for BETs that have been computed with the established changing parameter for *Case 1* for years 2023, 2030 and 2040. In addition to this, *Figure 26* illustrates the comparison between the *Base Case* and *Case 1* in terms of TCO.

TCO considering the changing parameter (500 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	358.453	20.000	76.000	0,26	9,5%	5	119.993	119.259	1,41
	2030								
BET	177.448	20.000	53.000	0,26	9,5%	5	110.551	119.259	0,98
	2040								
BET	180.510	20.000	47.000	0,26	9,5%	5	114.964	119.259	1,03

Table 157. TCO for Case 1 BETs with a 500 km daily driving range in €/km for years 2023, 2030 and 2040.

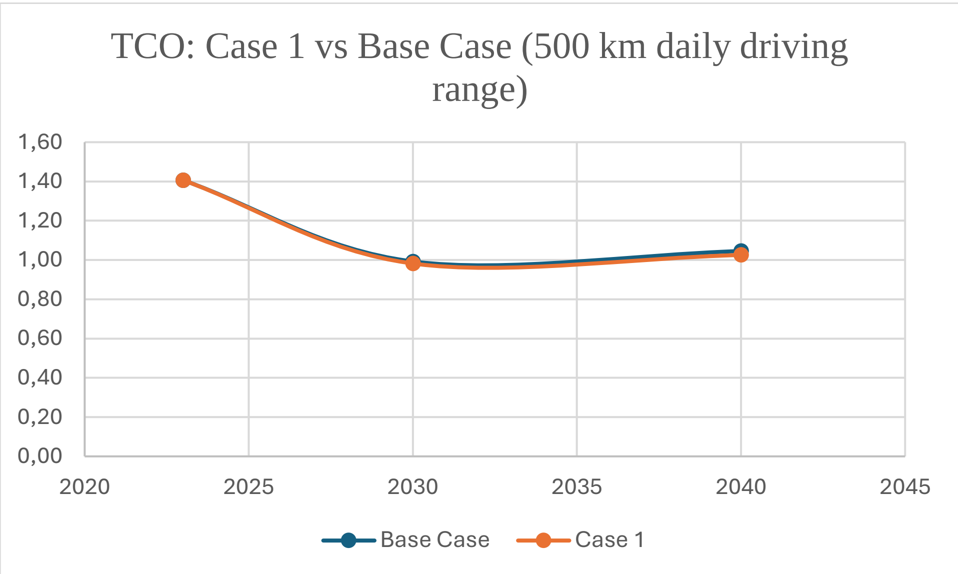

Figure 26. Comparison between the Base Case and Case 1 in terms of TCO for BETs with a 500 km daily driving range in €/km for years 2023, 2030 and 2040.

As it is shown in *Table 157*, for *Case 1* the TCO for BETs with a 500 km daily driving range is expected to vary from 1.41 €/km in 2023 to 0.98 €/km for 2030 and to 1.03 €/km for 2040. These estimates are slightly below the values obtained in the *Base Case* as it is shown on *Figure 26* for 2030 and 2040. Comparing the two cases in terms of TCO it can be computed that the TCO of *Case 1* is 1 % and 1,9 % lower than that of the *Base Case* for 2030 and 2040 respectively. Additionally, for 2030 and 2040 battery electric trucks continue to be the most competitive ones in terms of TCO, as it occurred in the *Base Case* for trucks with a 500 km daily driving range.

For battery electric trucks with an 800 km daily driving range, their TCO for years 2023, 2030 and 2040 for *Case 1* can be seen in *Table 158*. In addition to this, in *Figure 27* the comparison between the *Base Case* and *Case 1* in terms of TCO for this daily driving range is shown.

TCO considering the changing parameter (800 km driving range) (€/km)								
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	486.920	20.000	72.000	0,26	9,5%	5	145.667	158.349	1,40
	2030								
BET	222.243	20.000	71.000	0,26	9,5%	5	130.196	158.349	0,89
	2040								
BET	213.766	20.000	66.000	0,26	9,5%	5	134.430	158.349	0,90

Table 158. TCO for Case 1 BETs with an 800 km daily driving range in €/km for years 2023, 2030 and 2040.

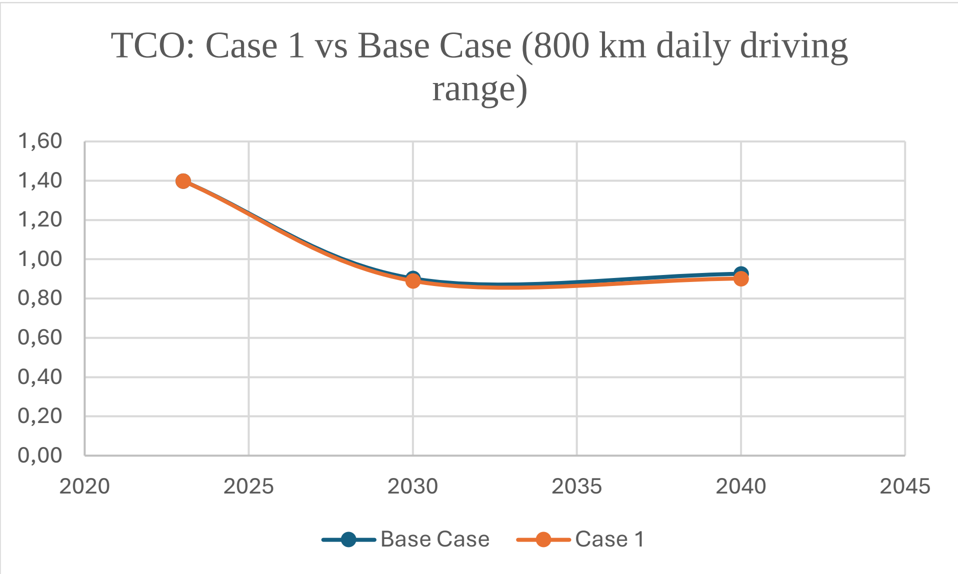

Figure 27. Comparison between the Base Case and Case 1 in terms of TCO for BETs with an 800 km daily driving range in €/km for years 2023, 2030 and 2040.

As it can be observed in *Table 158*, for *Case 1* the TCO for BETs with an 800 km daily driving range is estimated to change from 1.40 €/km in 2023 to 0.89 €/km for 2030 and to 0.90 €/km for 2040. As it is showed in *Figure 27*, these predictions are below the values obtained in the *Base Case* for the 2023-2040 period. In addition to this, when comparing the two cases in terms of TCO for 800 km daily driving range trucks, the TCO of *Case 1* is 1.4 % and 2.6 % lower than that of the *Base Case* for 2030 and 2040 respectively, which are larger decrements than the ones calculated for trucks with a daily driving range of 500 km. Additionally, for 2030 and 2040 BETs continue to be the most competitive technology in terms of TCO, as it happened in the *Base Case* for trucks with an 800 km daily driving range.

When it comes to battery electric trucks with a 1,000 km daily driving range, *Table 159* shows their TCO for years 2023, 2030 and 2040 for *Case 1*. Moreover, *Figure 28* displays the comparison between the *Base Case* and *Case 1* in terms of TCO for trucks with the previously mentioned daily driving range.

TCO considering the changing parameter (1000 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	561.503	20.000	64.000	0,26	9,5%	5	225.571	201.444	1,51
	2030								
BET	254.025	20.000	81.000	0,26	9,5%	5	193.908	201.444	0,98
	2040								
BET	237.360	20.000	76.000	0,26	9,5%	5	198.120	201.444	0,97

Table 159. TCO for Case 1 BETs with a 1,000 km daily driving range in €/km for years 2023, 2030 and 2040.

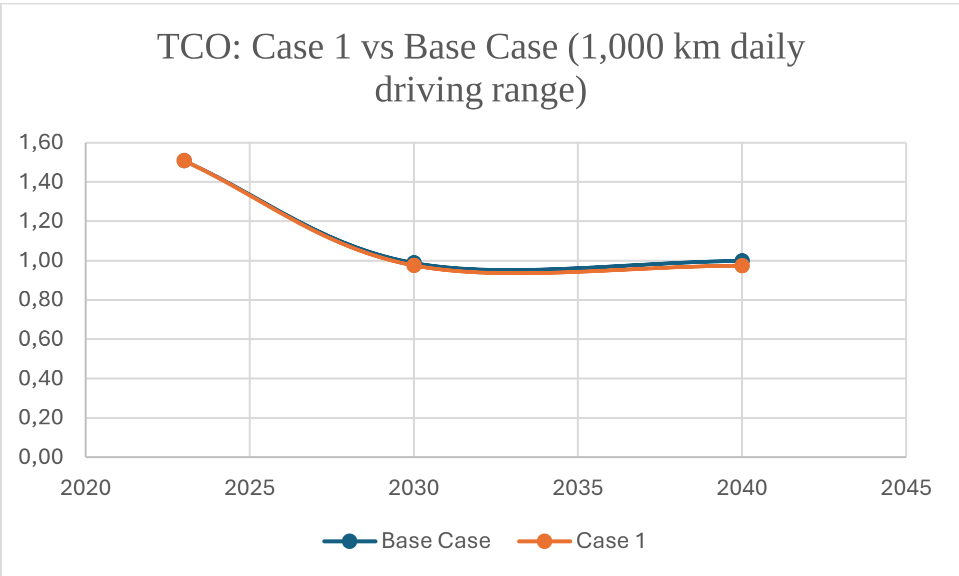

Figure 28. Comparison between the Base Case and Case 1 in terms of TCO for BETs with a 1,000 km daily driving range in €/km for years 2023, 2030 and 2040.

As its can be seen in *Table 159*, for *Case 1* the TCO for battery electric trucks with a 1,000 km daily driving range is estimated to decrease from 1.51 €/km in 2023 to 0.98

€/km for 2030 and to 0.97 €/km for 2040. When comparing the values obtained in the Base Case with the ones of *Case 1* it can be observed in *Figure 28* that these estimates from Case 1 are lower for 2030 and 2040. Studying both cases in terms of TCO for 1,000 km daily driving range trucks, the TCO of *Case 1* is around 1.3 % and 2.4 % lower than that of the *Base Case* for 2030 and 2040 respectively, which are slightly higher than the decrements obtained for trucks with 500 km daily driving ranges but slightly lower than those obtained for trucks with 800 km daily driving ranges. Moreover, for 2030 battery electric trucks continue to be the third most competitive technology as it occurred in the *Base Case* for trucks with a 1,000 km daily driving range. For 2040 they are the second most competitive one if CO_2 road charges are applied, otherwise they are the fourth most competitive one, which is what happened in the *Base Case* as well.

4.3. CASE 2 RESULTS: PRICE VARIATIONS IN THE FCET FUEL CELL SYSTEM

The near market sources expect a decrease in the retail unitary prices of fuel cell systems for 2030 and 2040 according to papers [7], [9]. Moreover, this paper also provides price ranges for the unitary fuel cell system in 2023 that suggest that there could be options in the market with a retail price lower than the one selected. Therefore, for *Case 2* optimistic values from [7], [9] have been selected. The previously mentioned sources estimate that the retail unitary prices of fuel cell systems will be on average of 538 €2020/kW for 2023, of 216 €2020/kW for 2030 and of 125 €2020/kW for 2040.

Taking into consideration the annual Spanish inflation rate between 2020 and 2023 (1 €2020 equals 1,157 €2023) the estimated values are of 622.5 €/kW for 2023, of 249.9 €/kW for 2030 144.6 €/kW for 2040. These unitary retail prices for the fuel cell system are gathered in *Table 160*. [57]

Compared to those of the *Base Case, Case 2* unitary retail prices are a 48.7 %, a 26.2 % and 45.1 % lower for years 2023, 2030 and 2040 respectively, which translates into noticeable decreases in the total retail price of the fuel cell system throughout the 2023-2040 period.

Retail price for the fuel cell unit system (€/kW)			
	2023	2030	2040
Near market	622,5	249,9	144,6

Table 160. Selected unitary retail prices of the fuel cell system of FCETs in €/kW for years 2023, 2030 and 2040 for Case 2. [7], [9]

Table 161 shows the total retail price of the fuel cell system in € for years 2023, 2030 and 2040. It is worth to mention that the fuel cell system size used for computing the different retail prices are the same as the ones used for the *Base Case*.

Total retail price of the fuel cell unit system (€)			
Component	**2023**	**2030**	**2040**
Fuel cell unit	112.043,88	44.984,16	26.032,50

Table 161. Total unitary retail prices of fuel cell system of FCETs in €/kW for years 2023, 2030 and 2040 for Case 1. [5], [7], [9], [39], [44], [45], [57]

4.3.1. CAPEX RESULTS

The CAPEX of FCETs with a 500 km daily driving range for years 2023, 2030 and 2040 computed for *Case 2* can be seen in *Table 162*. Additionally, *Figure 29* illustrates the comparison between the *Base Case* and *Case* 2 in terms of CAPEX.

CAPEX considering the changing parameter (500 km driving range) (€)				
	Powertrain	**Energy storage**	**Rest of the truck**	**CAPEX**
	2023			
FCET	191.016,88	76.953,65	80.601,08	348.571,60
	2030			
FCET	88.233,52	32.706,83	85.213,13	206.153,48
	2040			
FCET	69.019,26	27.480,38	102.077,90	198.577,54

Table 162. CAPEX for Case 2 FCETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

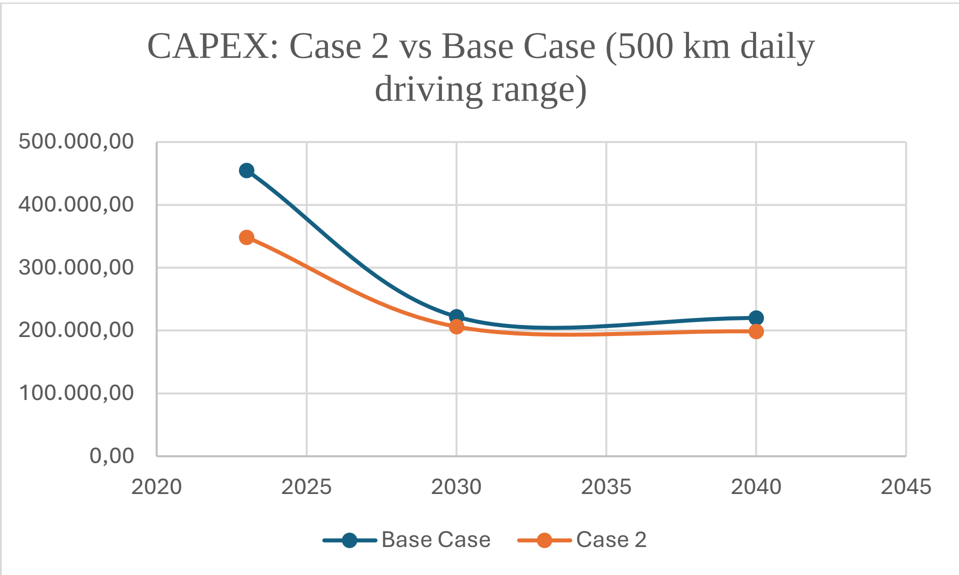

Figure 29. Comparison between the Base Case and Case 2 in terms of CAPEX for FCETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 162*, for *Case 2* the CAPEX for FCTs with a 500 km daily driving range is estimated to decrease from €348,571.60 in 2023 to €206,153.48 for 2030 and to €198,577.54 for 2040. These estimates are below the values obtained in the *Base*

Case, especially for year 2023, as it is shown in *Figure 29*. When comparing the two cases in terms of CAPEX, the CAPEX of *Case 2* is around 23.4 % lower for 2023, whereas for 2030 and 2040 this difference decreases to 7.2 % and 9.7 % respectively.

For fuel cell trucks with an 800 km daily driving range, *Table163* shows their CAPEX for years 2023, 2030 and 2040 for *Case 2*. In addition to this, in *Figure 30* the comparison between the *Base Case* and *Case 2* in terms of CAPEX is displayed.

CAPEX considering the changing parameter (800 km driving range) (€)				
	Powertrain	Energy storage	Rest of the truck	CAPEX
	2023			
FCET	191.016,88	124.835,91	80.601,08	396.453,87
	2030			
FCET	88.233,52	53.520,26	85.213,13	226.966,92
	2040			
FCET	69.019,26	43.436,74	102.077,90	214.533,89

Table 163. CAPEX for Case 2 FCETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

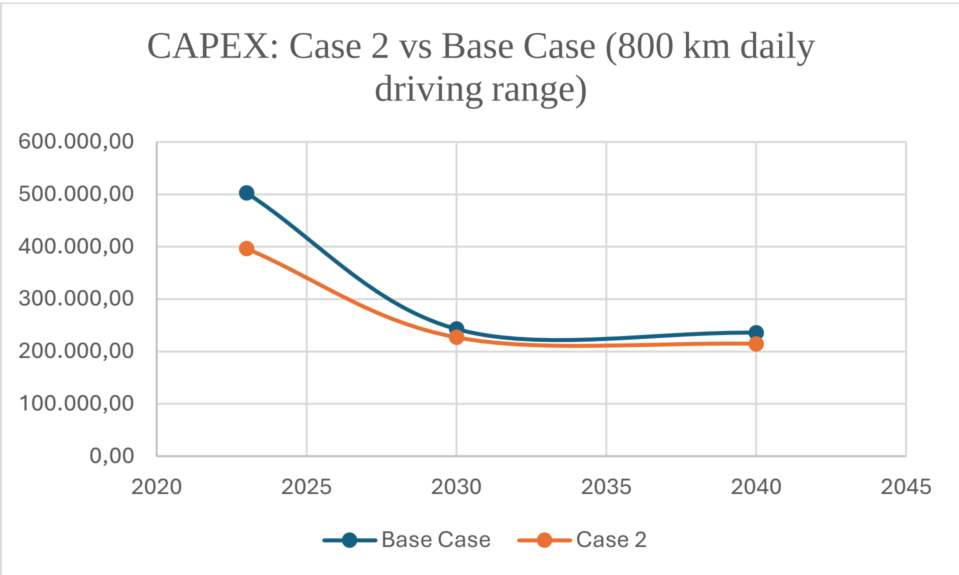

Figure 30. Comparison between the Base Case and Case 2 in terms of CAPEX for FCETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 163*, for *Case 2* the CAPEX for FCETs with an 800 km daily driving range is estimated to decrease from €396,453.87 in 2023 to €226,966.92 for 2030 and to €214,533.89 for 2040. All of these estimates are below the values obtained for the *Base Case*, although the largest difference can be found when comparing year 2023, as it can be seen in *Figure 30*. Moreover, making the comparison between the two cases in terms of CAPEX for 800 km daily driving range trucks, the CAPEX of *Case 2* for year 2023 is approximately 21.2 % lower, while for 2030 and 2040 this variation reduces to around 6.6 % and 9 % respectively, which is slightly less than the decrements obtained for trucks with a daily driving range of 500 km.

When it comes to FCETs with a 1,000 km daily driving range, *Table 164* shows their CAPEX for years 2023, 2030 and 2040 for *Case 2*. Furthermore, *Figure 31* illustrates the comparison between the *Base Case* and *Case 2* in terms of CAPEX for trucks with the previously mentioned daily driving range.

CAPEX considering the changing parameter (1000 km driving range) (€)				
	Powertrain	Energy storage	Rest of the truck	CAPEX
	2023			
FCET	191.016,88	147.066,97	80.601,08	418.684,92
	2030			
FCET	88.233,52	65.413,66	85.213,13	238.860,31
	2040			
FCET	69.019,26	54.074,30	102.077,90	225.171,46

Table 164. CAPEX for Case 2 FCETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

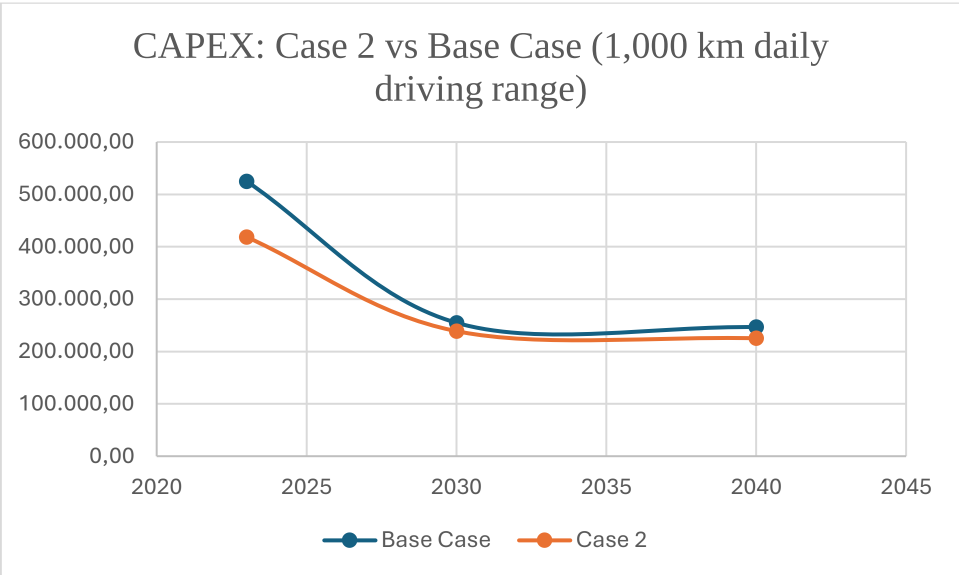

Figure 31. Comparison between the Base Case and Case 2 in terms of CAPEX for FCETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

Looking at *Table 164*, the CAPEX estimates of FCETs with a 1,000 km daily driving range for *Case 2* can be seen. As it is shown, the CAPEX is expected to decrease from €418,684.92 in 2023 to €238,860.31 for 2030 and to €225,171.46 for 2040. Compared to the values obtained in the *Base Case*, these estimates are lower for the 2023-2040 period as it can be seen in *Figure 31*. Analysing both cases in terms of CAPEX for 1,000 km daily driving range trucks, the CAPEX of *Case 1* is around 20.3 % lower than that of the *Base Case* for 2023, yet for 2030 and 2040 this reduction is about 6.3 % and 8.7 %

respectively, which is slightly lower than the decrements obtained for trucks with 500 km and 800 km daily driving ranges.

4.3.2. OPEX RESULTS

For *Case 2* the OPEX stays the same as in the *Base Case*.

4.3.3. TCO RESULTS

In the *Base Case* there were two OPEXs (OPEX_1 and OPEX_2) as in one of them the CO_2 road charges already approved by the European Parliament that should be implemented from 2023 onwards are considered in the other one they are not. As FCETs are considered a zero-emission technology and as a result are exempted from these charges, both OPEXs as well as TCOs are the same and consequently have been unified in OPEX 1 & 2 and TCO 1 & 2 as it can be observed on *Tables 165, 166 and 167*.

Focusing on trucks with a 500 km daily driving range, *Table 165* shows the TCOs for FCETs that have been computed with the selected changing parameter for *Case 2* for years 2023, 2030 and 2040. Additionally, *Figure 32* illustrates the comparison between the *Base Case* and *Case 2* in terms of TCO.

TCO considering the changing parameter (500 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	348.572	20.000	106.000	0,26	9,5%	5	190.601	119.259	1,80
	2030								
FCET	206.153	20.000	62.000	0,26	9,5%	5	139.307	119.259	1,22
	2040								
FCET	198.578	20.000	58.000	0,26	9,5%	5	127.404	119.259	1,13

Table 165. TCO for Case 2 FCETs with a 500 km daily driving range in €/km for years 2023, 2030 and 2040.

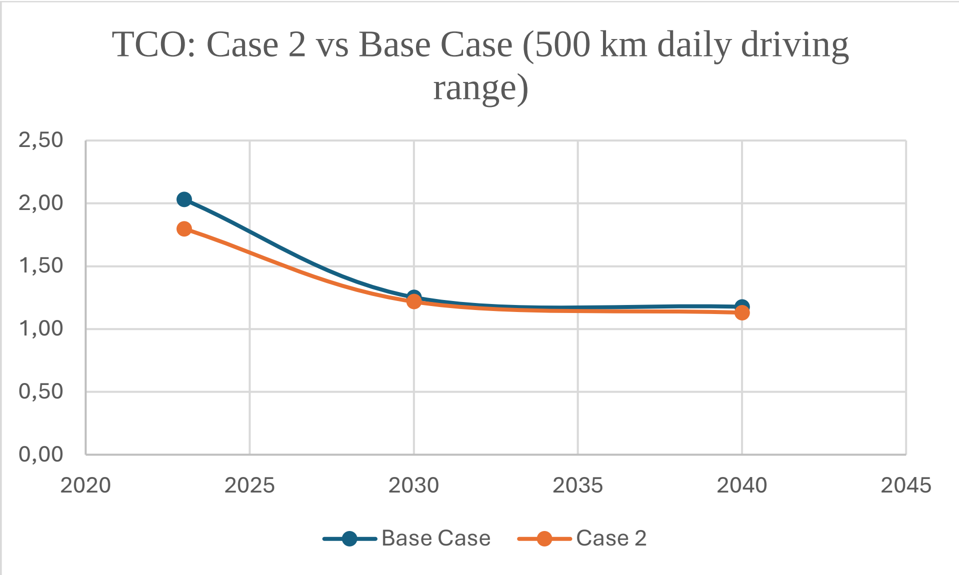

Figure 32. Comparison between the Base Case and Case 2 in terms of TCO for FCETs with a 500 km daily driving range in €/km for years 2023, 2030 and 2040.

As it is shown in *Table 165*, for *Case 2* the TCO for FCETs with a 500 km daily driving range is expected to decrease from 1.80 €/km in 2023 to 1.22 €/km for 2030 and to 1.13 €/km for 2040. These estimates are below the values obtained in the *Base Case*, especially for year 2023, as it is shown in *Figure 32*. Comparing the two cases in terms of TCO it can be computed that the TCO of *Case 2* is approximately 11.4 % lower than that of the *Base Case* for 2023, while it is around 2.8 % and 4 % lower for 2030 and 2040 respectively.

Additionally, for 2023 FCETs continue to be the less competitive technology in terms of TCO and for years 2030 and 2040 they maintain the positions they held on the TCO rankings in the *Base Case*, achieving their best record for 2040, when they are the second most competitive technology after BETs.

For fuel cell trucks with an 800 km daily driving range, their TCO for years 2023, 2030 and 2040 for *Case 2* can be seen in *Table 166*. In addition to this, in *Figure 33* the comparison between the *Base Case* and *Case 2* in terms of TCO for this daily driving range is shown.

TCO considering the changing parameter (800 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	396.454	20.000	125.000	0,26	9,5%	5	245.473	158.349	1,68
	2030								
FCET	226.967	20.000	75.000	0,26	9,5%	5	170.063	158.349	1,09
	2040								
FCET	214.534	20.000	71.000	0,26	9,5%	5	152.449	158.349	0,99

Table 166. TCO for Case 2 FCETs with an 800 km daily driving range in €/km for years 2023, 2030 and 2040.

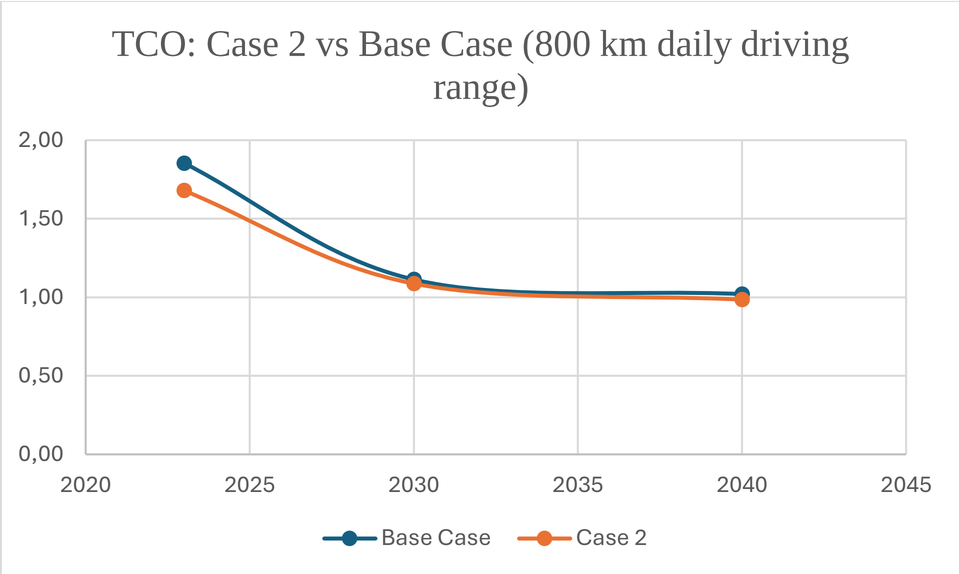

Figure 33. Comparison between the Base Case and Case 2 in terms of TCO for FCETs with an 800 km daily driving range in €/km for years 2023, 2030 and 2040.

As it can be seen in *Table 166*, for *Case 2* the TCO for FCETs with an 800 km daily driving range is estimated to decrease from 1.68 €/km in 2023 to 1.09 €/km for 2030 and to 0.99 €/km for 2040. As it is shown in *Figure 33*, these predictions are below the values obtained in the *Base Case* for the 2023-2040 period. In addition to this, when comparing the two cases in terms of TCO, for 800 km daily driving range trucks, the TCO of *Case 2* is around 9.4 % lower for 2023 than that of the *Base Case*, while it is about 2.4 % and 3.4% lower for years 2030 and 2040 respectively, which are lower decrements than the ones calculated for trucks with a daily driving range of 500 km.

Further still, for 2023 FCETs continue to be the less competitive technology in terms of TCO and for years 2030 and 2040 they occupy the same positions as in the *Base Case* on the TCO rankings, being 2040 the year in which they reach their best position by having the second most competitive TCO after BETs.

When it comes to fuel cell trucks with a 1,000 km daily driving range, *Table 167* shows their TCO for years 2023, 2030 and 2040 for *Case 2*. Moreover, *Figure 34* displays the comparison between the *Base Case* and *Case 2* in terms of TCO for trucks with the previously mentioned daily driving range.

TCO considering the changing parameter (1000 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	418.685	20.000	98.000	0,26	9,5%	5	290.922	201.444	1,54
	2030								
FCET	238.860	20.000	79.000	0,26	9,5%	5	196.707	201.444	0,97
	2040								
FCET	225.171	20.000	74.000	0,26	9,5%	5	173.726	201.444	0,87

Table 167. TCO for Case 2 FCETs with a 1,000 km daily driving range in €/km for years 2023, 2030 and 2040.

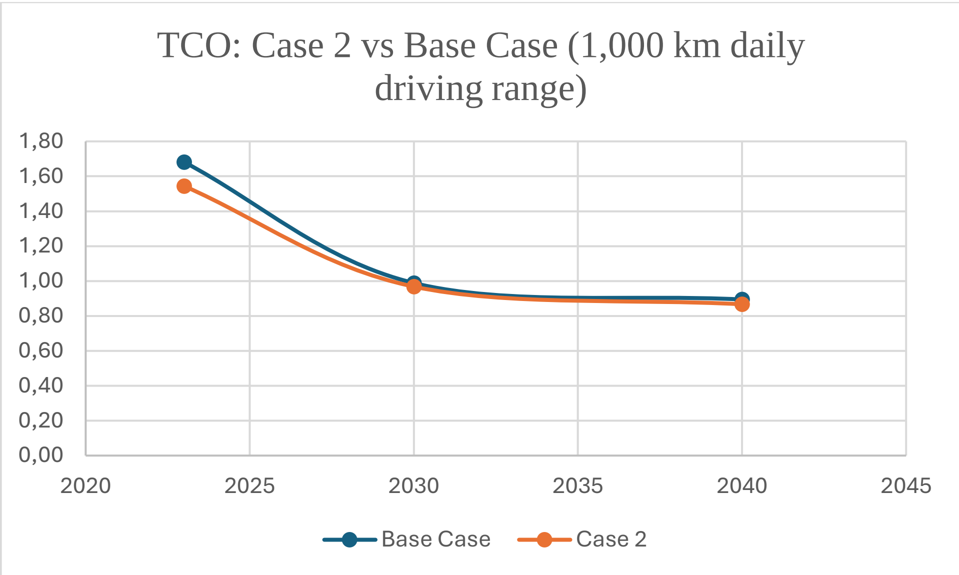

Figure 34. Comparison between the Base Case and Case 2 in terms of TCO for FCETs with a 1,000 km daily driving range in €/km for years 2023, 2030 and 2040.

As its can be seen in *Table 167*, for *Case 2* the TCO for fuel cell trucks with a 1,000 km daily driving range is estimated to decrease from 1.54 €/km in 2023 to 0.97 €/km for 2030 and to 0.87 €/km for 2040. When comparing the values obtained in the *Base Case* with the ones of *Case 2* it can be observed in *Figure 34* that these estimates from *Case 2* are lower, especially for 2023. Studying both cases in terms of TCO for 1,000 km daily driving range trucks, the TCO of *Case 2* is around 8.2 % lower than that of the *Base Case* for 2023, yet for 2030 and 2040 it is approximately 2.1 % and 3.1 % lower respectively, which are slightly lower decrements than the ones obtained for trucks with 500 km and 800 km daily driving ranges.

Moreover, for 2023 fuel cell trucks continue to be the technology with the highest TCO and consequently the less competitive one. However, for 2030 the TCO rankings change between the *Base Case* and *Case 2* as FCETs become more competitive than BETs, turning into the third most competitive technology after HVO and diesel trucks. Furthermore, for year 2040 FCETs clearly continue to be the most competitive technology like in the *Base Case*, as its TCO_1 (CO_2 charges applied) and TCO_2 (no CO_2 fees considered) are around 12.4 % and 6.6 % lower than those of diesel trucks, which are the technology with the second lowest TCOs for this year.

4.4. CASE 3 RESULTS: CHANGES ON DIESEL PRICE

For the *Base Case* a weighted average diesel retail price of 1.22 €/l excluding VAT was selected for trucks with 500 km and 800 km daily driving ranges and a weighted average diesel retail price of 1.17 €/l excluding VAT was established for trucks with a 1,000 km daily driving range.

However, considering the increase in the retail diesel price that have been taking pace in Spain for the past years especially after the outbreak of the Ukrainian war -in which diesel price skyrocketed-, it has been determined that a negative scenario needs to be analysed. Therefore, using the values provided by paper [9] a diesel retail price of 1,75 €/l excluding VAT applied to all driving ranges will be selected for years 2023, 2030 and 2040 for *Case 3*.

This, which is illustrated in *Table 168*, implies around a 30.3 % increase for trucks with 500 km and 800 km daily driving ranges and around a 33.1 % increase for trucks with a 1,000 km daily driving range compared to the diesel prices selected for the *Base Case*.

Selected retail price (€/l)			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Diesel	1,75	1,75	1,75

Table 168. Selected diesel retail price in €/l for years 2023, 2030 and 2040 for Case 3. [9]

Table 169 shows the trucks' diesel annual consumption based on the trucks' daily driving range for years 2023, 2030 and 2040 in €. It is needed to point out that the fuel consumption and the travelled annual kilometres of each driving range used for computing the total annual fuel cost is the same as in the *Base Case*.

Truck diesel annual consumption based on driving range (€)				
Technology	Class	2023	2030	2040
Diesel	5-LH (500 km)	64.072	48.419	48.419
	5-LH (800 km)	85.073	64.290	64.290
	5-LH (1000 km)	108.226	81.786	81.786

Table 169. Truck's diesel annual consumption based on its daily driving range for years 2023, 2030 and 2040 established for Case 3 in €. [4], [5], [9]

4.4.1. CAPEX Results

For *Case 3* the CAPEX stays the same as in the *Base Case*.

4.4.2. OPEX Results

For 5-LH diesel trucks *Tables 170, 171 and 172* show the results for the OPEXs for years 2023, 2030 and 2040.

For the *Base Case* as well as for *Case 3*, OPEX_1 corresponds to the diesel trucks' OPEX considering the CO_2 road fees that the European Parliament has already approved and are supposed to be applied in the different European member states from 2023 onwards. OPEX_2 refers to the diesel trucks' OPEX without applying such CO_2 road fees as there are member states which are postponing this measure.

Table 170 shows the computed OPEX_1 and OPEX_2 for diesel trucks with a 500 km daily driving range for years 2023, 2030 and 2040 for *Case 3*. Moreover, *Figure 35* illustrates the comparison between the *Base Case* and *Case 3* in terms of OPEXs.

OPEX considering the changing parameter (500 km driving range) (€)								
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
	2023							
Diesel	15.265,18	9.540,74	64.072,01	53.164,80	1.733,00	22.062,95	165.838,67	156.297,93
	2030							
Diesel	15.265,18	9.540,74	48.419,24	56.214,44	1.904,00	22.062,95	153.406,54	143.865,81
	2040							
Diesel	15.265,18	9.540,74	48.419,24	60.877,00	1.904,00	22.062,95	158.069,10	148.528,36

Table 170. OPEX_1 and OPEX_2 for Case 3 for diesel trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

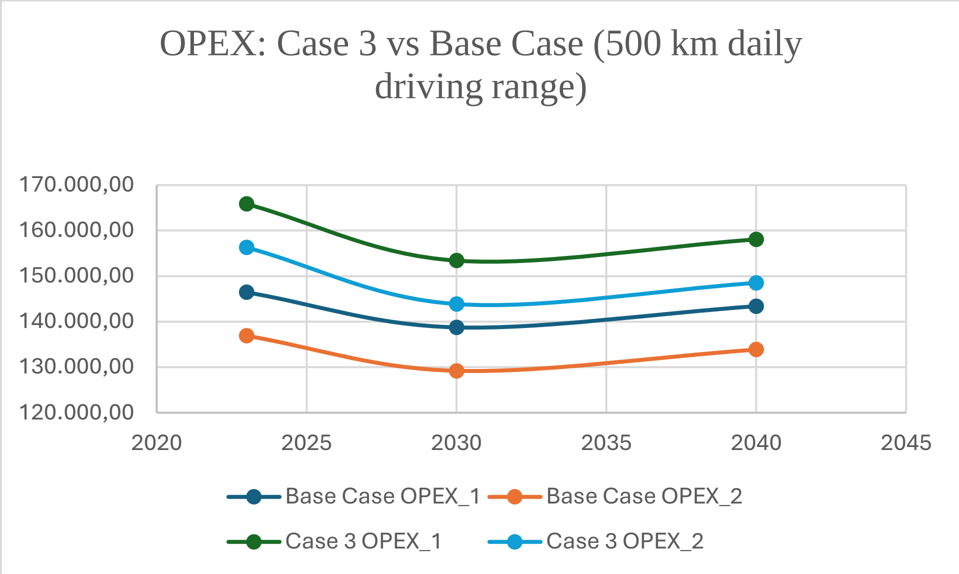

Figure 35. Comparison between the Base Case and Case 3 in terms of OPEX_1 and OPEX_2 for diesel trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 170*, for *Case 3* OPEX_1 for diesel trucks with a 500 km daily driving range is estimated to change from €165,838.67 in 2023 to €153,406.54 for 2030 and to €158,069.10 for 2040. These estimates are higher than the values obtained for OPEX_1 in the *Base Case* as it is shown in *Figure 35*. When comparing the two cases in terms of OPEX_1, the OPEX_1 of *Case 3* is around 11.7 % higher than that of the *Base Case* for 2023, while for 2030 and 2040 it is approximately 9.6 % and 9.3 % higher respectively.

Additionally, OPEX_2 for *Case 3* and the *Base Case* can also be seen in *Table 170*. As it is shown, OPEX_2 for diesel trucks with a 500 km daily driving range is estimated to vary from €156,297.93 in 2023 to €143,865.81 for 2030 and to €148,528.36 for 2040. These estimates are higher than the values obtained for OPEX_1 and OPEX_2 in the *Base Case* but lower than those of OPEX_1 for *Case 3* as it can be observed in *Figure 35*. When comparing the two cases in terms of OPEX_2, the OPEX_2 of *Case 3* is approximately 12.4 % higher than that of the *Base Case*, while for 2030 and 2040 it is about 10.2 % and 9.9 % higher respectively.

Furthermore, it can be seen in *Figure 35* that the lowest OPEX for diesel trucks with a daily driving range of 500 km corresponds to OPEX_2 from the *Base Case*, whereas OPEX_1 from *Case 3* is the highest one followed by OPEX_2 from *Case 3* as well.

For diesel trucks with an 800 km daily driving range, *Table 171* shows their OPEX_1 and OPEX_2 for years 2023, 2030 and 2040 for *Case 3*. In addition to this, in *Figure 36* the comparison between the *Base Case* and *Case 3* in terms of OPEXs is displayed.

OPEX considering the changing parameter (800 km driving range) (€)								
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
	2023							
Diesel	22.802,31	12.667,95	85.073,22	53.164,80	3.766,00	29.294,64	206.768,92	194.100,97
	2030							
Diesel	22.802,31	12.667,95	64.289,86	56.214,44	4.109,00	29.294,64	189.378,20	176.710,25
	2040							
Diesel	22.802,31	12.667,95	64.289,86	60.877,00	4.109,00	29.294,64	194.040,76	181.372,81

Table 171. OPEX_1 and OPEX_2 for Case 3 for diesel trucks with an 800 km daily driving range in € for years 2023, 2030 and 2040.

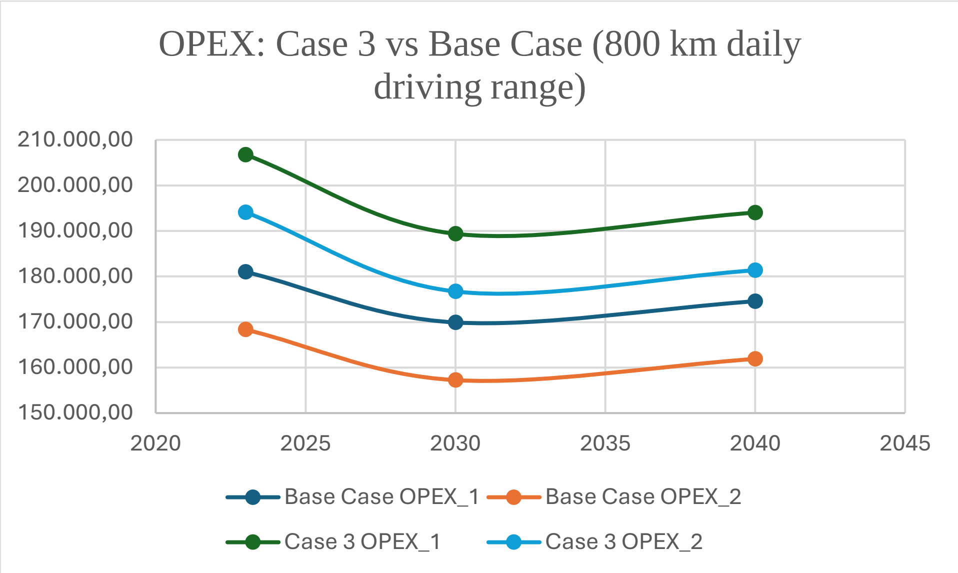

Figure 36. Comparison between the Base Case and Case 3 in terms of OPEX_1 and OPEX_2 for diesel trucks with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 171*, for *Case 3* the OPEX_1 for diesel trucks with an 800 km daily driving range is estimated to vary from €206,768.92 in 2023 to €189,378.20 for 2030 and to €194,040.76 for 2040. All of these estimates are above the values obtained for the *Base Case*, as it can be seen in *Figure 36*. Moreover, making the comparison between the two cases in terms of OPEX_1 for 800 km daily driving range trucks, the OPEX_1 of *Case 3* for year 2023 is approximately 12.5 % higher than that of the *Base Case*, whereas for 2030 and 2040 this increase reduces to around 10.3 % and 10 % respectively, which are larger increments than the ones calculated for diesel trucks with a daily driving range of 500 km.

Furthermore, as *Table 171* shows, for *Case 3* the OPEX_2 for diesel trucks with an 800 km daily driving range is estimated to change from €194,100.97 in 2023 to €176,710.25 for 2030 and to €181,372.81 for 2040. As it can be seen in *Figure 36*, these estimates are all higher than the values obtained for the *Base Case*. Comparing the *Base Case* and *Case*

3 in terms of OPEX_2 for 800 km daily driving range trucks, it can be calculated that the OPEX_2 of *Case 3* for year 2023 is around 13.3 % higher than that of the *Base Case*, whereas for 2030 and 2040 this increase reduces to around 11 % and 10.7 % respectively, which are larger increments than the ones calculated for diesel trucks with a daily driving range of 500 km.

Moreover, it can be seen in *Figure 36* that the lowest OPEX for diesel trucks with a daily driving range of 800 km corresponds to OPEX_2 from the *Base Case*, whereas OPEX_1 from *Case 3* is the highest one followed by OPEX_2 from *Case 3* as well.

When it comes to diesel trucks with a 1,000 km daily driving range, *Table 172* shows their OPEX_1 and OPEX_2 for years 2023, 2030 and 2040 for *Case 3*. Furthermore, *Figure 37* illustrates the comparison between the *Base Case* and *Case 3* in terms of OPEXs for trucks with the previously mentioned daily driving range.

OPEX considering the changing parameter (1000 km driving range) (€)								
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX_1	OPEX_2
	2023							
Diesel	30.619,52	16.115,54	108.225,90	53.164,80	3.766,00	37.267,18	249.158,93	233.043,39
	2030							
Diesel	30.619,52	16.115,54	81.786,35	56.214,44	4.109,00	37.267,18	226.112,02	209.996,48
	2040							
Diesel	30.619,52	16.115,54	81.786,35	60.877,00	4.109,00	37.267,18	230.774,57	214.659,04

Table 172. OPEX_1 and OPEX_2 for Case 3 for diesel trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

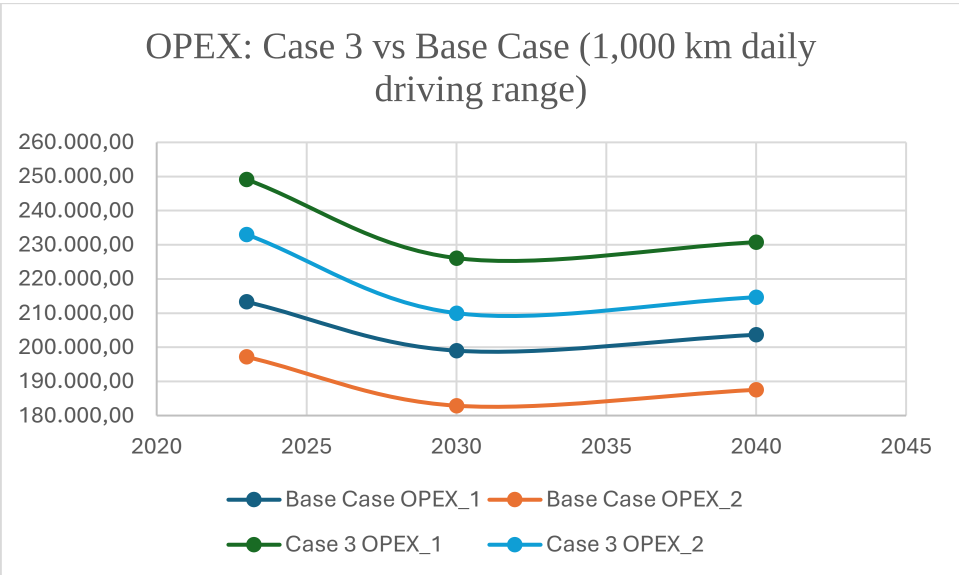

Figure 37. Comparison between the Base Case and Case 3 in terms of OPEX_1 and OPEX_2 for diesel trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

Focusing on *Table 172*, the OPEX_1 and OPEX_2 estimates of diesel trucks with a 1,000 km daily driving range for *Case 3* can be observed. As it is shown, the OPEX_1 is expected to vary from €249,158.93 in 2023 to €226,112.02 for 2030 and to €230,774.57 for 2040. Compared to the values obtained in the *Base Case*, these estimates are higher as it can be seen in *Figure 37*. Analysing both cases in terms of OPEX_1 for 1,000 km daily driving range trucks, the OPEX_1 of *Case 3* is around 14.4 % higher than that of the *Base Case* for 2023, yet for 2030 and 2040 this increase is about 12 % and 11.7 % respectively, which is slightly higher than the variations obtained for trucks with 500 km and 800 km daily driving ranges.

Furthermore, as it can be observed in *Table 172*, the OPEX_2 is estimated to change from €233,043.39 in 2023 to €209,996.48 for 2030 and to €214,659.04 for 2040. As it is shown in *Figure 37*, these values are above the ones computed for the *Base Case*. Comparing both cases in terms of OPEX_2 for 1,000 km daily driving range trucks, the OPEX_2 for *Case 3* is around 15.4 % higher than that of the *Base Case* for 2023, yet for 2030 and 2040 this increase is about 12.9 % and 12.6 % respectively, which are higher increments than the ones obtained for trucks with 500 km and 800 km daily driving ranges.

Additionally, it can be seen in *Figure 37* that the lowest OPEX for diesel trucks with a daily driving range of 1,000 km corresponds to OPEX_2 from the *Base Case*, while OPEX_1 from *Case 3* is the highest one followed by OPEX_2 from *Case 3* as well.

4.4.3. TCO RESULTS

For the *Base Case* as well as for *Case 3*, OPEX_1 corresponds to the diesel trucks' OPEX considering the CO_2 road fees that the European Parliament has already approved and are supposed to be applied in the different European member states from 2023 onwards. OPEX_2 refers to the diesel trucks' OPEX without applying such CO_2 road fees as there are member states which are postponing this measure.

Consequently, there are two different TCOs for both, the *Base Case* and *Case 3*, when it comes to diesel trucks as they are affected by these CO_2 road charges. TCO_1 is the one computed applying CO_2 road fees, while for TCO_2 these fees are not considered. *Tables 173, 174 and 175* show the results for the OPEX for years 2023, 2030 and 2040.

Focusing on diesel trucks with a 500 km daily driving range, *Table 173* shows the TCO_1 and TCO_2 for diesel trucks that have been computed with the selected changing parameter for *Case 3* for years 2023, 2030 and 2040. Moreover, *Figure 38* illustrates the comparison between the *Base Case* and *Case 3* in terms of TCOs.

TCO considering the changing parameter (500 km driving range) (€/km)											
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
	2023										
Diesel	137.243	-	42.000	0,26	9,5%	5	165.839	156.298	119.259	1,31	1,25
	2030										
Diesel	157.479	-	43.000	0,26	9,5%	5	153.407	143.866	119.259	1,27	1,21
	2040										
Diesel	193.184	-	43.000	0,26	9,5%	5	158.069	148.528	119.259	1,38	1,32

Table 173. TCO_1 and TCO_2 for Case 3 for diesel trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

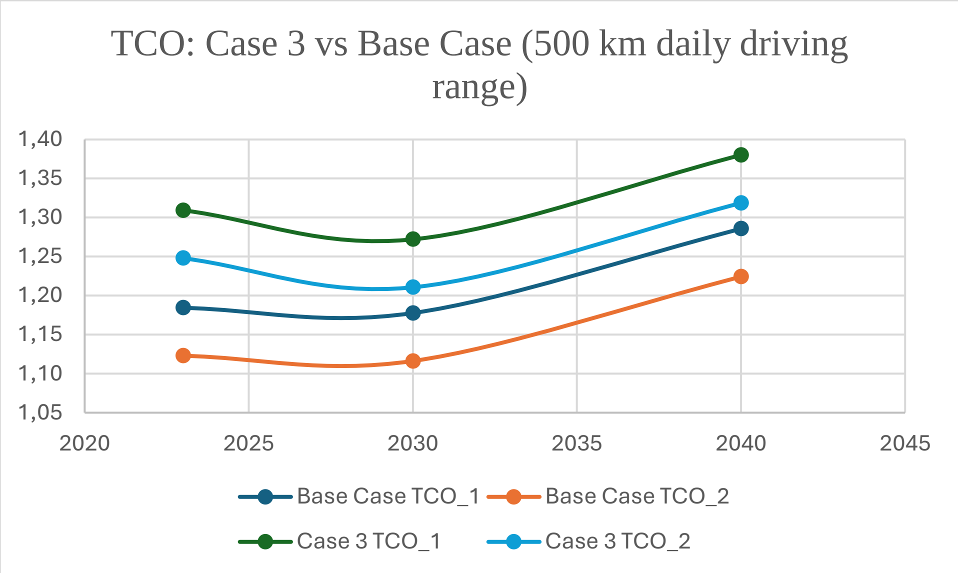

Figure 38. Comparison between the Base Case and Case 3 in terms of TCO_1 and TCO_2 for diesel trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 173*, for *Case 3* the TCO_1 for diesel trucks with a 500 km daily driving range is expected to change from 1.31 €/km in 2023 to 1.27 €/km for 2030 and to 1.38 €/km for 2040. These estimates are above the values computed for the *Base Case*, as it can be seen in *Figure 38*. Comparing the two cases in terms of TCO_1 it can be calculated that the TCO_1 of *Case 3* for this daily driving range is approximately 9.5 % higher for 2023, while it is around 7.4 % and 6.8 % higher for 2030 and 2040 respectively.

Additionally, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_1, which was their position at the *Base Case.* On the contrary, for year 2030 diesel trucks become the technology with the third highest TCO_1, which is higher than that of FCETs, while at the *Base Case* it was the technology with the second lowest TCO_1. Further still, for year 2040 diesel trucks stop being the third most competitive technology, as it happened at the *Base Case,* to become the technology with the third highest TCO_1.

Moving on to the analysis of TCO_2, as it can be seen in *Table 173*, for *Case 3* the TCO_2 for diesel trucks with a 500 km daily driving range is expected to change from 1.25 €/km in 2023 to 1.21 €/km for 2030 and to 1.32 €/km for 2040. These values are higher than the ones computed for the *Base Case*, as it is shown in *Figure 38*. Comparing the two cases in terms of TCO_2 it can be calculated that the TCO_2 of *Case 3* is around 10 % higher for 2023, whereas it is around 7.8 % and 7.2 % higher for 2030 and 2040 respectively.

Furthermore, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_2, which was the position that they held at the *Base Case.* However, for year 2030 diesel trucks become the technology with the third lowest TCO_2, while at the *Base Case* it was the technology with the second lowest TCO_2. Moreover, for year 2040 diesel trucks become the technology with the third highest TCO_2 while on the *Base Case* they were the third most competitive technology.

For diesel trucks with an 800 km daily driving range, their TCO_1 and TCO_2 for years 2023, 2030 and 2040 for *Case* 3 can be seen in *Table 174.* In addition to this, in *Figure 39* the comparison between the *Base Case* and *Case* 3 in terms of TCOs for this daily driving range is shown.

TCO considering the changing parameter (800 km driving range) (€/km)											
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
	2023										
Diesel	138.288	-	48.000	0,26	9,5%	5	206.769	194.101	158.349	1,18	1,12
	2030										
Diesel	158.720	-	49.000	0,26	9,5%	5	189.378	176.710	158.349	1,13	1,07
	2040										
Diesel	194.772	-	49.000	0,26	9,5%	5	194.041	181.373	158.349	1,21	1,15

Table 174. TCO_1 and TCO_2 for Case 3 for diesel trucks with an 800 km daily driving range in € for years 2023, 2030 and 2040.

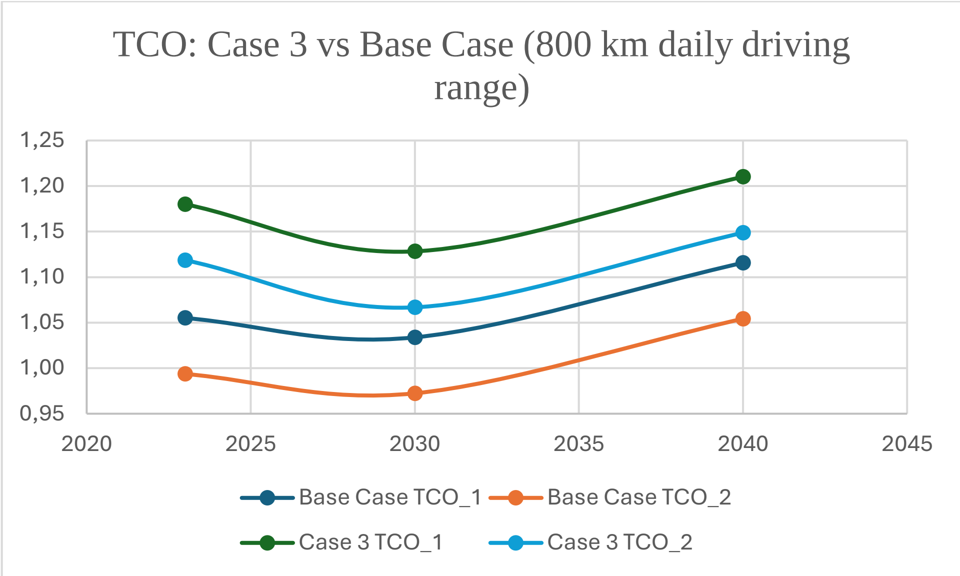

Figure 39. Comparison between the Base Case and Case 3 in terms of TCO_1 and TCO_2 for diesel trucks with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 174*, for *Case 3* the TCO_1 for diesel trucks with an 800 km daily driving range is expected to change from 1.18 €/km in 2023 to 1.13 €/km for 2030 and to 1.21 €/km for 2040. These estimates are above the values computed for the *Base Case*, as it can be seen in *Figure 39*. Comparing the two cases in terms of TCO_1 it can be calculated that the TCO_1 of *Case 3* for an 800 km daily driving range is approximately 10.6 % higher for 2023, while it is around 8.4 % and 7.8 % higher for 2030 and 2040 respectively. These increments are higher than the ones for trucks with a 500 km daily driving range throughout the 2023-2040 period.

In addition to this, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_1, which was their position at the *Base Case.* In contrast, for year 2030 diesel trucks become the technology with the third highest TCO_1, which is higher than that of FCETs, while at the *Base Case* it was the technology with the second lowest TCO_1. Moreover, for 2040 diesel trucks become the technology with the third highest TCO_1 whereas on the *Base Case* they were the third most competitive technology.

Analysing the TCO_2 for trucks with an 800 km daily driving range, as it can be seen in *Table 174*, for *Case 3* the TCO_2 for diesel trucks with this daily driving range is expected to change from 1.12 €/km in 2023 to 1.07 €/km for 2030 and to 1.15 €/km for 2040. These values are higher than the ones computed for the *Base Case*, as it is displayed in *Figure 39*. Comparing the two cases in terms of TCO_2, it can be computed that the TCO_2 of *Case 3* for this studied daily driving range is around 11.2 % higher for 2023, whereas it is around 8.9 % and 8.2 % higher for 2030 and 2040 respectively. These increments are higher than the ones for trucks with a 500 km daily driving range for the analysed years.

Moreover, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_2, which was the position that they held at the *Base Case*. On the contrary, for year 2030 diesel trucks become the technology with the third lowest TCO_2, while at the *Base Case* it was the technology with the second lowest TCO_2. Additionally, for year 2040 diesel trucks stop being the third most competitive technology, as it occurred at the *Base Case,* to become the technology with the third highest TCO_2.

When it comes to diesel trucks with a 1,000 km daily driving range, *Table 175* shows their TCO_1 and TCO_2 for years 2023, 2030 and 2040 for *Case 3*. Moreover, *Figure 40* displays the comparison between the *Base Case* and *Case 3* in terms of TCOs for trucks with the previously mentioned daily driving range.

TCO considering the changing parameter (1000 km driving range) (€/km)											
	CAPEX	SUB	SV	CRF	i	N	OPEX 1	OPEX 2	AKT	TCO 1	TCO 2
	2023										
Diesel	138.984	-	48.000	0,26	9,5%	5	249.159	233.043	201.444	1,09	1,03
	2030										
Diesel	159.547	-	49.000	0,26	9,5%	5	226.112	209.996	201.444	1,03	0,97
	2040										
Diesel	195.832	-	49.000	0,26	9,5%	5	230.775	214.659	201.444	1,09	1,03

Table 175. TCO_1 and TCO_2 for Case 3 for diesel trucks with a1,000 km daily driving range in € for years 2023, 2030 and 2040.

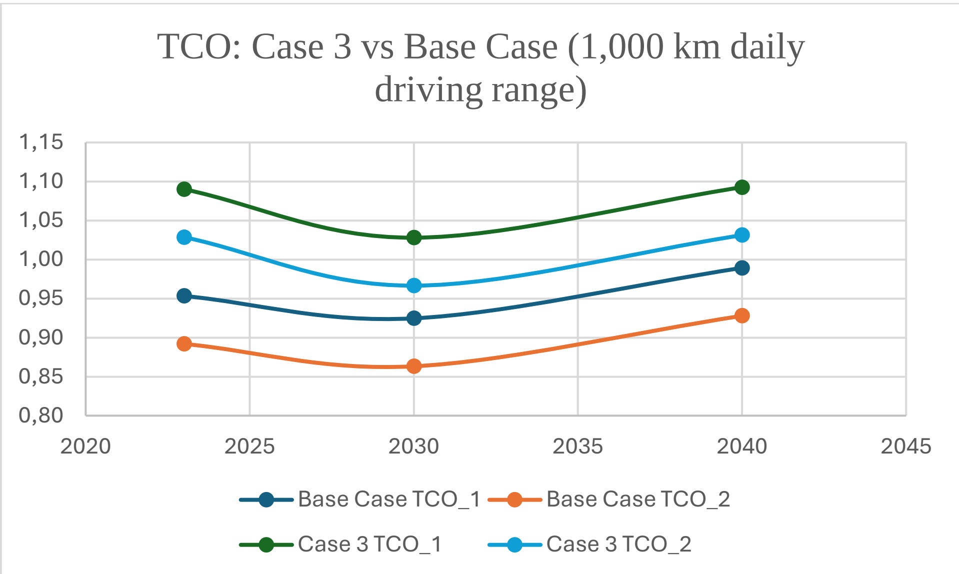

Figure 40. Comparison between the Base Case and Case 3 in terms of TCO_1 and TCO_2 for diesel trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 175*, for *Case 3* the TCO_1 for diesel trucks with a 1,000 km daily driving range is expected to change from 1.09 €/km in 2023 to 1.03 €/km for

2030 and to 1.09 €/km for 2040. These estimates are above the values computed for the *Base Case*, as it can be seen in *Figure 40*. Comparing the two cases in terms of TCO_1 it can be calculated that the TCO_1 of *Case 3* for a 1,000 km daily driving range is approximately 12.5 % higher for 2023, while it is around 10.1 % and 9.5 % higher for 2030 and 2040 respectively. These increments are higher than the ones for trucks with 500 km and 800 km daily driving ranges for the 2023-2040 period.

In addition to this, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_1, which was what happened at the *Base Case.* However, for year 2030 diesel trucks become the technology with the third highest TCO_1, which is higher than that of FCETs, while at the *Base Case* it was the technology with the lowest TCO_1. Furthermore, for 2040 diesel trucks become the technology with the third highest TCO_1 whereas on the *Base Case* they were the second most competitive technology.

Focusing on the TCO_2 for trucks with a 1,000 km daily driving range, as it can be observed in *Table 175*, for *Case 3* the TCO_2 for diesel trucks with this daily driving range is expected to change from 1.03 €/km in 2023 to 0.97 €/km for 2030 and to 1.03 €/km for 2040. These values are higher than the ones computed for the *Base Case*, as it is shown in *Figure 40*. Comparing the two cases in terms of TCO_2, it can be computed that the TCO_2 of *Case 3* for this studied daily driving range is around 13.3 % higher for 2023, whereas it is around 10.7 % and 10 % higher for 2030 and 2040 respectively. These increments are higher than the ones for trucks with 500 km and 800 km daily driving ranges for the studied years.

Furthermore, for 2023 diesel trucks become the second most competitive technology rather than the first one in terms of TCO_2, which was the position that they held at the *Base Case.* On the contrary, for year 2030 diesel trucks become the technology with the second lowest TCO_2, whereas at the *Base Case* it was the technology with the lowest TCO_2. Additionally, for year 2040 diesel trucks stop being the second most competitive technology, as it happened at the *Base Case,* to become the technology with the third highest TCO_2.

4.5. CASE 4 RESULTS: DECREASE OF ELECTRICITY PRICES

For the *Base Case* the electricity retail price selected considering the cost of the charging infrastructure and excluding VAT was of 0.252 €/kWh for BETs with a 500 km daily driving range of 0.24 €/kWh for BETs with an 800 km daily driving range and of 0.452 €/kWh for BETs with a 1,000 km daily driving range.

These electricity retail prices were assumed constant throughout the studied period (2023-2040) for the *Base Case*. However, due to the increase of the electricity production coming from renewable energy sources, which may lead to a decrease in the electricity prices, a scenario in which the electricity retail price reduces in 25 % for 2030 and in 50 % for 2040 compared to the selected 2023 value for the *Base Case* has been developed. *Table 176* shows the unitary electricity prices selected for *Case 4* in €/kWh. [10]

Selected electricity retail prices (€/kWh)			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Charging cost (2023)	0,252	0,24	0,452
Charging cost (2030)	0,189	0,18	0,339
Charging cost (2040)	0,126	0,12	0,226

Table 176. Selected electricity retail price in €/kWh for years 2023, 2030 and 2040 for Case 4. [10]

Table 177 shows the BETs' electricity annual consumption based on the trucks' daily driving range for years 2023, 2030 and 2040 in €. It is needed to point out that the electricity consumption and the travelled annual kilometres of each driving range used for computing the total annual electricity cost is the same as in the *Base Case*.

Truck electricity annual consumption based on driving range (€)				
Technology	Class	2023	2030	2040
BET	5-LH (500 km)	39.370	21.638	14.426
	5-LH (800 km)	50.355	27.648	18.432
	5-LH (1000 km)	120.645	67.948	45.299

Table 177. Truck's electricity annual consumption based on its daily driving range for years 2023, 2030 and 2040 established for Case 4 in €.

4.5.1. CAPEX RESULTS

For *Case 4* the CAPEX stays the same as in the *Base Case*.

4.5.2. OPEX RESULTS

For 5-LH battery electric trucks *Tables 178, 179 and 180* show the results for the OPEX for years 2023, 2030 and 2040.

At the Base Case there were two different OPEXs (OPEX_1 and OPEX_2) depending on whether the CO_2 road charges approved by the European Parliament were applied or not. As BETs are considered zero-emission trucks they are exempted from these fees so OPEX_1 and OPEX_2 have been joined into OPEX 1 & 2 as they have both the same value.

Table 178 shows the computed OPEX for battery electric trucks with a 500 km daily driving range for years 2023, 2030 and 2040 for *Case 4*. Moreover, *Figure 41* illustrates the comparison between the *Base Case* and *Case 4* in terms of OPEX.

OPEX considering the changing parameter (500 km driving range) (€)							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX 1 & 2
	2023						
BET	7.632,59	-	39.369,85	53.164,80	4.036,00	15.789,92	119.993,15
	2030						
BET	7.632,59	-	21.638,39	56.214,44	2.063,00	15.789,92	103.338,34
	2040						
BET	7.632,59	-	14.425,59	60.877,00	1.813,00	15.789,92	100.538,10

Table 178. OPEX for Case 4 for BETs trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

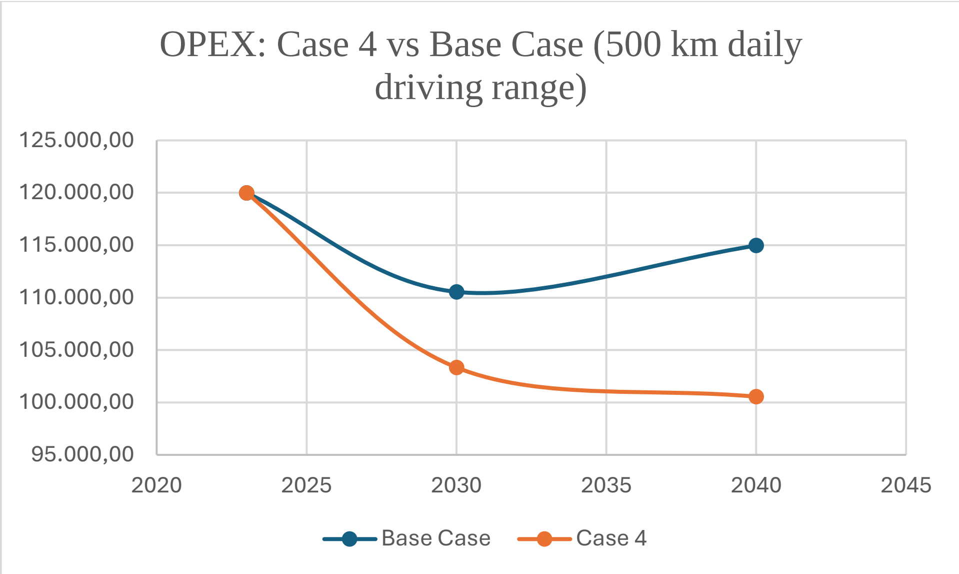

Figure 41. Comparison between the Base Case and Case 4 in terms of OPEX for BETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 178*, for *Case 4* OPEX for battery electric trucks with a 500 km daily driving range is estimated to change from €119,993.15 in 2023 to €103,338.34 for 2030 and to €100,538.10 for 2040. These estimates for 2030 and 2040 are lower than the ones obtained for the OPEX in the *Base Case* as it is shown in *Figure 41*. When comparing the two cases in terms of OPEX, the OPEX of *Case 4* is around 6.5 % and 12.5 % lower than that of the *Base Case* for years 2030 and 2040 respectively.

For BETs with an 800 km daily driving range, *Table 179* shows their OPEX for years 2023, 2030 and 2040 for *Case 4*. In addition to this, in *Figure 42* the comparison between the *Base Case* and *Case 4* in terms of OPEX is displayed.

OPEX considering the changing parameter (800 km driving range) (€)							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX 1 & 2
	2023						
BET	11.401,16	-	50.355,11	53.164,80	9.780,00	20.965,46	145.666,53
	2030						
BET	11.401,16	-	27.647,81	56.214,44	4.751,00	20.965,46	120.979,87
	2040						
BET	11.401,16	-	18.431,87	60.877,00	4.323,00	20.965,46	115.998,49

Table 179. OPEX for Case 4 for BETs trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

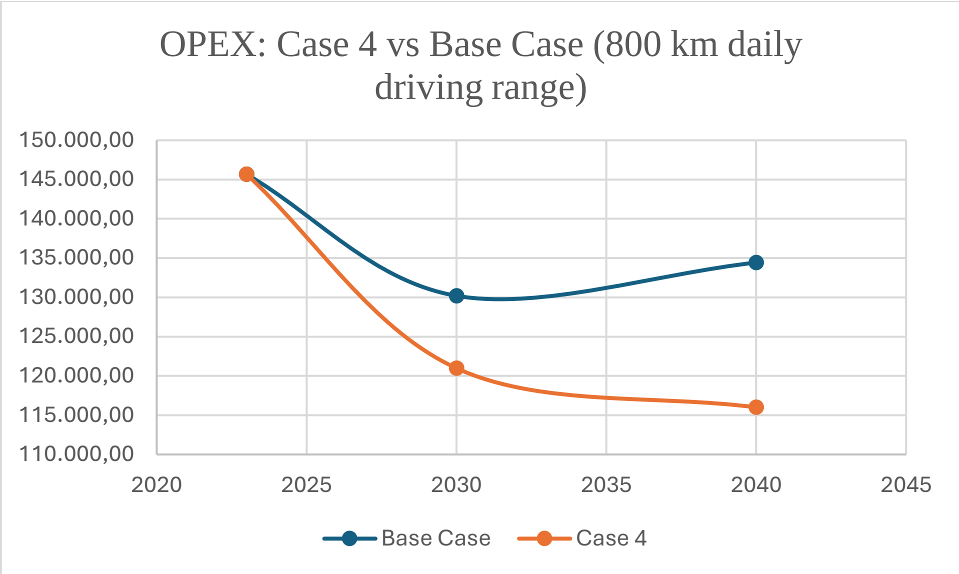

Figure 42. Comparison between the Base Case and Case 4 in terms of OPEX for BETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 179*, for *Case 4* the OPEX for BETs with an 800 km daily driving range is estimated to vary from €145,666.53 in 2023 to €120,979.87 for 2030 and to €115,998.49 for 2040. For years 2030 and 2040 these estimates are below the values obtained for the *Base Case*, as it can be seen in *Figure 42*. Moreover, making the comparison between the two cases in terms of OPEX for 800 km daily driving range trucks, the OPEX of *Case 4* is around 7.1 % and 13.7 % lower than that of the *Base Case* for years 2030 and 2040 respectively, which are larger decrements than the ones for trucks with a 500 km daily driving range.

When it comes to battery electric trucks with a 1,000 km daily driving range, *Table 180* shows their OPEX for years 2023, 2030 and 2040 for *Case 4*. Furthermore, *Figure 43* illustrates the comparison between the *Base Case* and *Case 4* in terms of OPEX for trucks with the previously mentioned daily driving range.

OPEX considering the changing parameter (1000 km driving range) (€)							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX 1 & 2
	2023						
BET	15.309,76	-	120.644,93	53.164,80	9.780,00	26.671,21	225.570,70
	2030						
BET	15.309,76	-	67.948,14	56.214,44	5.115,00	26.671,21	171.258,55
	2040						
BET	15.309,76	-	45.298,76	60.877,00	4.665,00	26.671,21	152.821,73

Table 180. OPEX for Case 4 for BETs trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

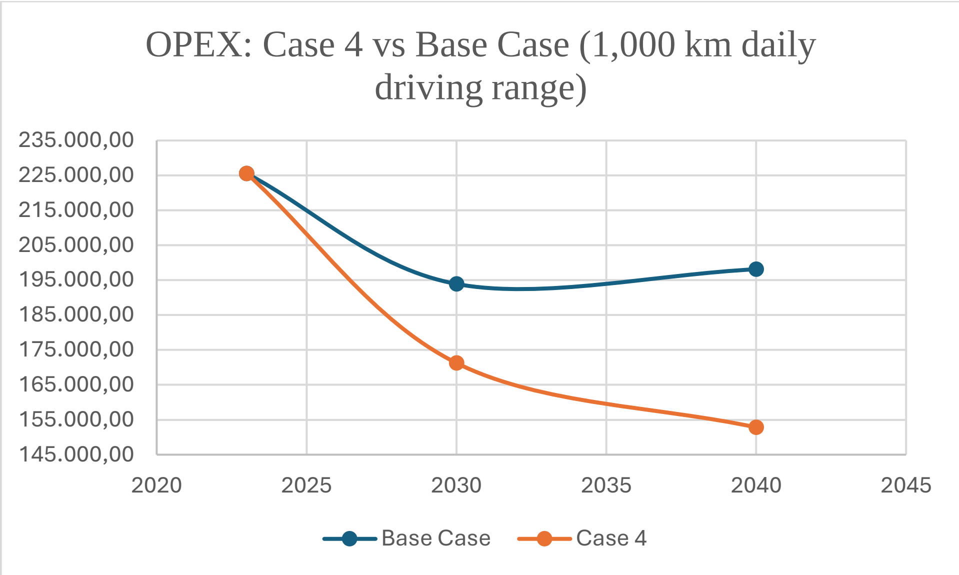

Figure 43. Comparison between the Base Case and Case 4 in terms of OPEX for BETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

Focusing on *Table 180*, the OPEX estimates of BETs with a 1,000 km daily driving range for *Case 4* can be observed. As it is shown, the OPEX is expected to vary from €225,570.70 in 2023 to €171,258.55 for 2030 and to €152,821.73 for 2040. Compared to the values obtained in the *Base Case*, these estimates are lower for 2030 and 2040 as it can be seen in *Figure 43*. Analysing both cases in terms of OPEX for 1,000 km daily driving range trucks, the OPEX of *Case 4* is around 11.7 % and 22.9 % lower than that of the *Base Case* for years 2030 and 2040 respectively, which are larger reductions than the ones obtained for trucks with 500 km and 800 km daily driving ranges.

4.5.3. TCO RESULTS

In the *Base Case* there were two OPEXs (OPEX_1 and OPEX_2) as in one of them the CO_2 road charges already approved by the European Parliament that should be implemented from 2023 onwards are considered but in the other one they are not. As

BETs are considered a zero-emission technology and as a result are exempted from these charges, both OPEXs as well as TCOs are the same and consequently have been unified in OPEX 1 & 2 and TCO 1 & 2 as it can be observed on *Tables 181, 182 and 183*.

For trucks with a 500 km daily driving range, *Table 181* shows the TCO for BETs that have been computed with the established changing parameter for *Case 4* for years 2023, 2030 and 2040. In addition to this, *Figure 44* illustrates the comparison between the *Base Case* and *Case 4* in terms of TCO.

TCO considering the changing parameter (500 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	358.453	20.000	76.000	0,26	9,5%	5	119.993	119.259	1,41
	2030								
BET	182.176	20.000	53.000	0,26	9,5%	5	103.338	119.259	0,95
	2040								
BET	189.700	20.000	47.000	0,26	9,5%	5	100.538	119.259	0,95

Table 181. TCO for Case 4 for BETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

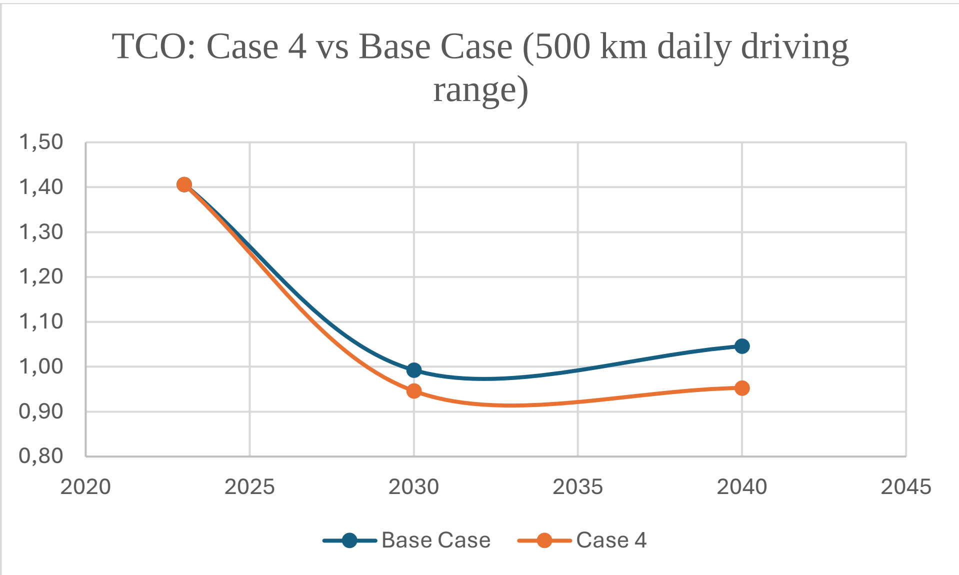

Figure 44. Comparison between the Base Case and Case 4 in terms of TCO for BETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 181*, for *Case 4* the TCO for battery electric trucks with a 500 km daily driving range is expected to change from 1.41 €/km in 2023 to 0.95 €/km for 2030 and to 0.95 €/km for 2040. These estimates are below the values computed for the *Base Case* for 2030 and 2040, as it can be seen in *Figure 44*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 4* for this daily driving range is approximately 4.7 % and 8.9 % lower than that of the *Base Case* for 2030 and 2040 respectively.

Additionally, for 2023 BETs continue to have the third highest TCO as the parameters for this year are the same as for the *Base Case*. Moreover, they continue to be the most competitive technology for 2030 and 2040 among trucks with 500 km daily driving ranges with even a larger margin (around a 19.7 % lower TCO_1 than that of diesel trucks which is the second most competitive technology for 2030 and about a 19 % lower TCO than that of FCETS, which is the second most competitive technology for 2040).

For BETs with an 800 km daily driving range, their TCO for years 2023, 2030 and 2040 for *Case 4* can be seen in *Table 182*. In addition to this, in *Figure 45* the comparison between the *Base Case* and *Case 4* in terms of TCO for this daily driving range is shown.

TCO considering the changing parameter (800 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	486.920	20.000	72.000	0,26	9,5%	5	145.667	158.349	1,40
	2030								
BET	229.862	20.000	71.000	0,26	9,5%	5	120.980	158.349	0,86
	2040								
BET	228.574	20.000	66.000	0,26	9,5%	5	115.998	158.349	0,84

Table 182. TCO for Case 4 for BETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

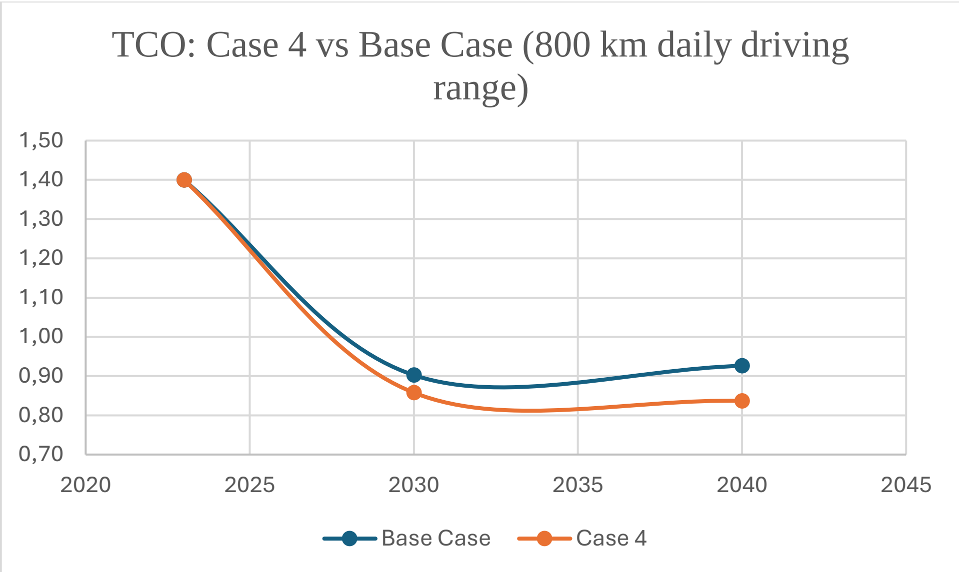

Figure 45. Comparison between the Base Case and Case 4 in terms of TCO for BETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 182,* for *Case 4* the TCO for battery electric trucks with an 800 km daily driving range is expected to change from 1.40 €/km in 2023 to 0.86 €/km for 2030 and to 0.84 €/km for 2040. These estimates are lower than the values computed for the *Base Case* for 2030 and 2040, as it is shown in *Figure 45*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 4* for this daily driving range is around 5 % and 9.7 % lower than that of the *Base Case* for 2030 and 2040 respectively, which imply higher decrements than those for trucks with a 500 km daily driving range.

Furthermore, for 2023 BETs continue to have the second highest TCO as the parameters for this year are the same as for the *Base Case*. In addition to this, they continue to be the most competitive technology for 2030 and 2040 among trucks with 800 km daily driving ranges with even a larger margin (around a 17 % lower TCO_1 than that of diesel trucks which is the second most competitive technology for 2030 and about an 18 % lower TCO than that of FCETS, which is the second most competitive technology for 2040).

When it comes to BETs with a 1,000 km daily driving range, *Table 183* shows their TCO for years 2023, 2030 and 2040 for *Case 4*. Moreover, *Figure 46* displays the comparison between the *Base Case* and *Case 4* in terms of TCO for trucks with the previously mentioned daily driving range.

TCO considering the changing parameter (1000 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
BET	561.503	20.000	64.000	0,26	9,5%	5	225.571	201.444	1,51
	2030								
BET	263.694	20.000	81.000	0,26	9,5%	5	171.259	201.444	0,90
	2040								
BET	256.154	20.000	76.000	0,26	9,5%	5	152.822	201.444	0,83

Table 183. TCO for Case 4 for BETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

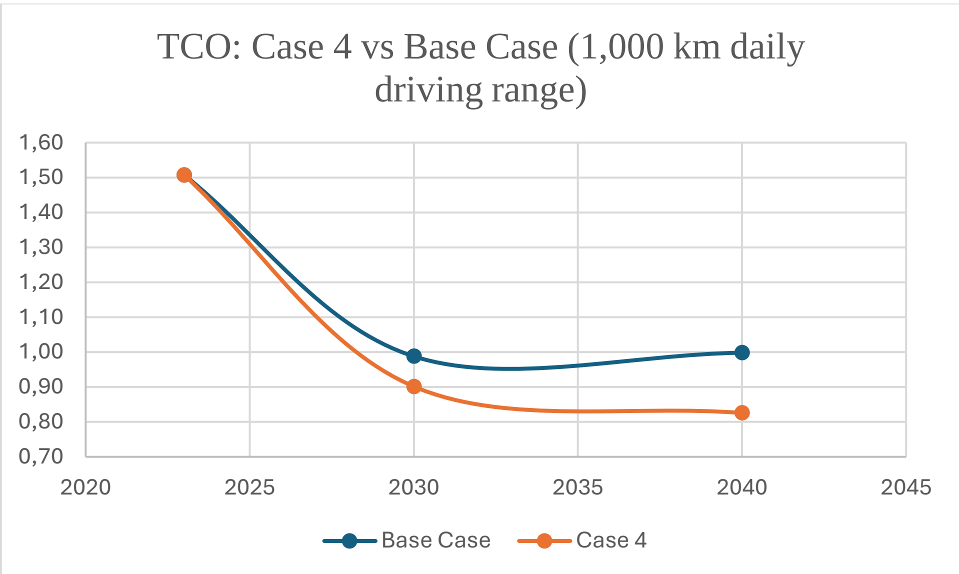

Figure 46. Comparison between the Base Case and Case 4 in terms of TCO for BETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

As it can be seen in *Table 183*, for *Case 4* the TCO for battery electric trucks with a 1,000 km daily driving range is expected to change from 1.51 €/km in 2023 to 0.90 €/km for 2030 and to 0.83 €/km for 2040. These estimates are below the values computed for the *Base Case* for 2030 and 2040, as it is shown in *Figure 46*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 4* for this daily driving range is approximately 8.7 % and 17.3 % lower than that of the *Base Case* for 2030 and 2040 respectively. These decrements are higher than the ones for trucks with 500 km and 800 km daily driving ranges.

In addition to this, for 2023 BETs continue to have the second highest TCO as the parameters for this year are the same as for the *Base Case*. Moreover, for 2030 they become the most competitive technology in terms of TCO_1 followed by diesel (at the *Base Case* BETs were the third most competitive one). However, if CO_2 road charges are not considered for 2030 BETs have the third lowest TCO_2, as it happened at the *Base Case*. On the contrary, for year 2040 BETs become the most competitive technology surpassing FCETs, which was the most competitive technology at the *Base Case* (the difference between these two technologies in terms of TCO is around 7.7 %).

4.6. CASE 5 RESULTS: DECREASE IN THE HYDROGEN PRICE

For the *Base Case* the at-the-pump hydrogen retail prices selected excluding VAT were an average made out of the values provided by different sources. However, there is a lot of uncertainty when it comes to at-the-pump hydrogen retail prices as at least in Spain there are very few hydrogen charging stations (only 9 in 2023). [11]

As a result, *Case 5* has been developed for providing a moderately optimistic scenario for the following decades. For this analysis, it has been assumed that there will be a 20 % decrease in the at-the-pump hydrogen retail prices for 2030 and 2040 compared to the selected prices for these two years in the *Base Case*. Nevertheless, for 2023 it has been assumed that the at-the-pump hydrogen retail price stays the same as that of the *Base Case* for each daily driving range. The unitary hydrogen retail prices based on year and daily driving range can be seen in *Table 184*. [9]

Selected hydrogen retail prices (€/kg)			
	5-LH (500 km)	5-LH (800 km)	5-LH (1000 km)
Green hydrogen (2023) (€/kg)	10,3	10,3	9,92
Green hydrogen (2030) (€/kg)	6,216	6,216	5,936
Green hydrogen (2040) (€/kg)	4,664	4,664	4,408

Table 184. Selected at-the-pump hydrogen retail price in €/kg for years 2023, 2030 and 2040 for Case 5. [9]

Table 185 shows the FCETs' hydrogen annual consumption based on the trucks' daily driving range for years 2023, 2030 and 2040 in €. It is needed to point out that the hydrogen consumption and the travelled annual kilometres of each driving range used for computing the total annual hydrogen cost is the same as in the *Base Case*.

Truck hydrogen annual consumption based on driving range (€)				
Technology	**Class**	**2023**	**2030**	**2040**
FCET	5-LH (500 km)	102.200	45.443	32.372
	5-LH (800 km)	137.167	60.633	43.205
	5-LH (1000 km)	170.457	73.899	52.212

Table 185. Truck's hydrogen annual consumption based on its daily driving range for years 2023, 2030 and 2040 established for Case 5 in €. [4], [5], [9], [39], [44]

4.6.1. CAPEX RESULTS

For *Case 5* the CAPEX stays the same as in the *Base Case*.

4.6.2. OPEX RESULTS

For 5-LH fuel cell trucks *Tables 186, 187 and 188* show the results for the OPEX for years 2023, 2030 and 2040.

At the *Base Case* there were two different OPEXs (OPEX_1 and OPEX_2) depending on whether the CO_2 road charges approved by the European Parliament were applied or not. As FCETs are considered zero-emission trucks they are exempted from these fees so OPEX_1 and OPEX_2 have been joined into OPEX 1 & 2 as they have both the same value.

Table 186 shows the computed OPEX for fuel cell trucks with a 500 km daily driving range for years 2023, 2030 and 2040 for *Case 5*. Moreover, *Figure 47* illustrates the comparison between the *Base Case* and *Case 5* in terms of OPEX.

OPEX considering the changing parameter (500 km driving range) (€)							
	Tolls	**CO2 charges**	**Fuel cost**	**Driver wage**	**Insurance**	**O&M**	**OPEX 1 & 2**
	2023						
FCET	7.632,59	-	102.200,36	53.164,80	5.540,00	22.062,95	190.600,70
	2030						
FCET	7.632,59	-	45.442,62	56.214,44	2.223,00	16.433,92	127.946,57
	2040						
FCET	7.632,59	-	32.372,29	60.877,00	1.995,00	16.433,92	119.310,79

Table 186. OPEX for Case 5 for FCETs trucks with a 500 km daily driving range in € for years 2023, 2030 and 2040.

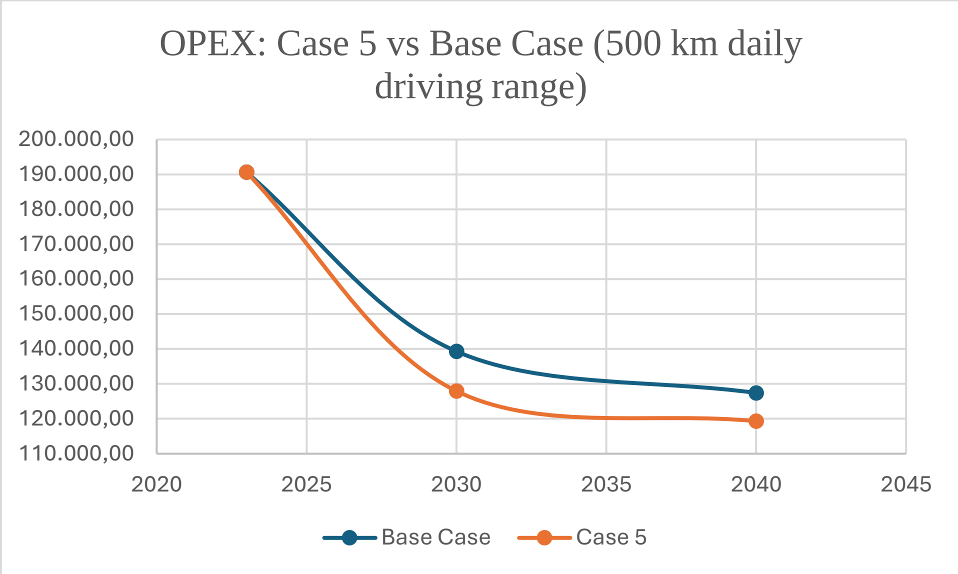

Figure 47. Comparison between the Base Case and Case 5 in terms of OPEX for FCETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 186*, for *Case 5* OPEX for fuel cell trucks with a 500 km daily driving range is estimated to change from €190,600.70 in 2023 to €127,946.57 for 2030 and to €119,310.79 for 2040. These estimates for 2030 and 2040 are lower than the ones obtained for the OPEX in the *Base Case* as it is shown in *Figure 47*. When comparing the two cases in terms of OPEX, the OPEX of *Case 5* is around 8.2 % and 6.4% lower than that of the *Base Case* for years 2030 and 2040 respectively.

For FCETs with an 800 km daily driving range, *Table 187* shows their OPEX for years 2023, 2030 and 2040 for *Case 5*. In addition to this, in *Figure 48* the comparison between the *Base Case* and *Case 5* in terms of OPEX is displayed.

OPEX considering the changing parameter (800 km driving range) (€)							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX 1 & 2
	2023						
FCET	11.401,16	-	137.167,00	53.164,80	14.445,00	29.294,64	245.472,60
	2030						
FCET	11.401,16	-	60.632,87	56.214,44	4.836,00	21.820,55	154.905,02
	2040						
FCET	11.401,16	-	43.204,68	60.877,00	4.344,00	21.820,55	141.647,39

Table 187. OPEX for Case 5 for FCETs trucks with an 800 km daily driving range in € for years 2023, 2030 and 2040.

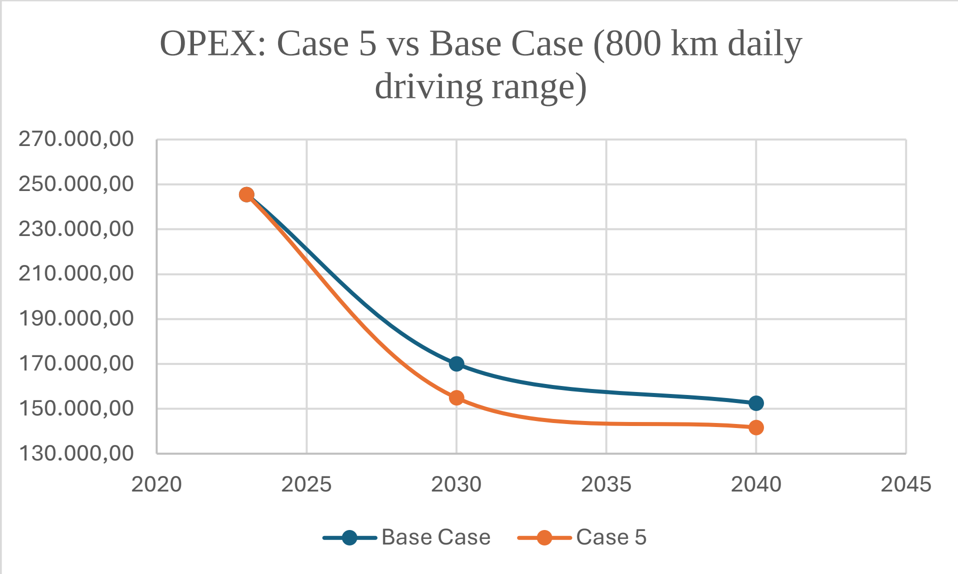

Figure 48. Comparison between the Base Case and Case 5 in terms of OPEX for FCETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 187*, for *Case 5* the OPEX for FCETs with an 800 km daily driving range is estimated to vary from €245,472.60 in 2023 to €154,905.02 for 2030 and to €141,647.39 for 2040. For years 2030 and 2040 these estimates are below the values obtained for the *Base Case*, as it can be seen in *Figure 48*. Moreover, making the comparison between the two cases in terms of OPEX, for 800 km daily driving range trucks, the OPEX of *Case 5* is around 8.9 % and 7.1 % lower than that of the *Base Case* for years 2030 and 2040 respectively, which are slightly larger decrements than the ones for trucks with a 500 km daily driving range.

When it comes to fuel cell trucks with a 1,000 km daily driving range, *Table 188* shows their OPEX for years 2023, 2030 and 2040 for *Case 5*. Furthermore, *Figure 49* illustrates the comparison between the *Base Case* and *Case 5* in terms of OPEX for trucks with the previously mentioned daily driving range.

OPEX considering the changing parameter (1000 km driving range) (€)							
	Tolls	CO2 charges	Fuel cost	Driver wage	Insurance	O&M	OPEX 1 & 2
	2023						
FCET	15.309,76	-	170.457,25	53.164,80	14.723,00	37.267,18	290.921,98
	2030						
FCET	15.309,76	-	73.898,76	56.214,44	5.050,00	27.759,01	178.231,97
	2040						
FCET	15.309,76	-	52.212,40	60.877,00	4.515,00	27.759,01	160.673,17

Table 188. OPEX for Case 5 for FCETs trucks with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

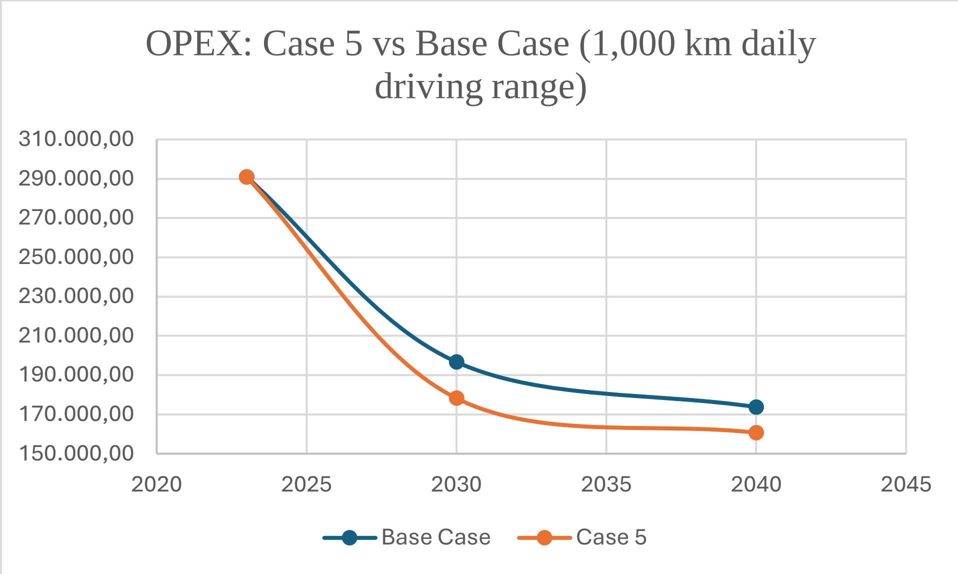

Figure 49. Comparison between the Base Case and Case 5 in terms of OPEX for FCETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

Focusing on *Table 188*, the OPEX estimates of FCETs with a 1,000 km daily driving range for *Case 5* can be observed. As it is shown, the OPEX is expected to vary from €290,921.98 in 2023 to €178,231.97 for 2030 and to €160,673.17 for 2040. Compared to the values obtained in the *Base Case*, these estimates are lower as it can be seen in *Figure 49*. Analysing both cases in terms of OPEX for 1,000 km daily driving range trucks, the OPEX of *Case 5* is around 9.4 % and 7.5 % lower than that of the *Base Case* for years 2030 and 2040 respectively, which are larger reductions than the ones obtained for trucks with 500 km and 800 km daily driving ranges.

4.6.3. TCO RESULTS

In the *Base Case* there were two OPEXs (OPEX_1 and OPEX_2) as in one of them the CO_2 road charges already approved by the European Parliament that should be implemented from 2023 onwards are considered but in the other one they are not. As FCETs are considered a zero-emission technology and as therefore are exempted from these charges, both OPEXs as well as TCOs are the same and consequently have been unified in OPEX 1 & 2 and TCO 1 & 2 as it can be observed in *Tables 189, 190 and 191*.

Focusing on trucks with a 500 km daily driving range, *Table 189* shows the TCO for FCETs that have been computed with the established changing parameter for *Case 5* for years 2023, 2030 and 2040. In addition to this, *Figure 50* illustrates the comparison between the *Base Case* and *Case 5* in terms of TCO.

TCO considering the changing parameter (500 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	454.920	20.000	106.000	0,26	9,5%	5	190.601	119.259	2,03
	2030								
FCET	222.114	20.000	62.000	0,26	9,5%	5	127.947	119.259	1,18
	2040								
FCET	219.922	20.000	58.000	0,26	9,5%	5	119.311	119.259	1,12

Table 189. TCO for Case 5 for FCETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

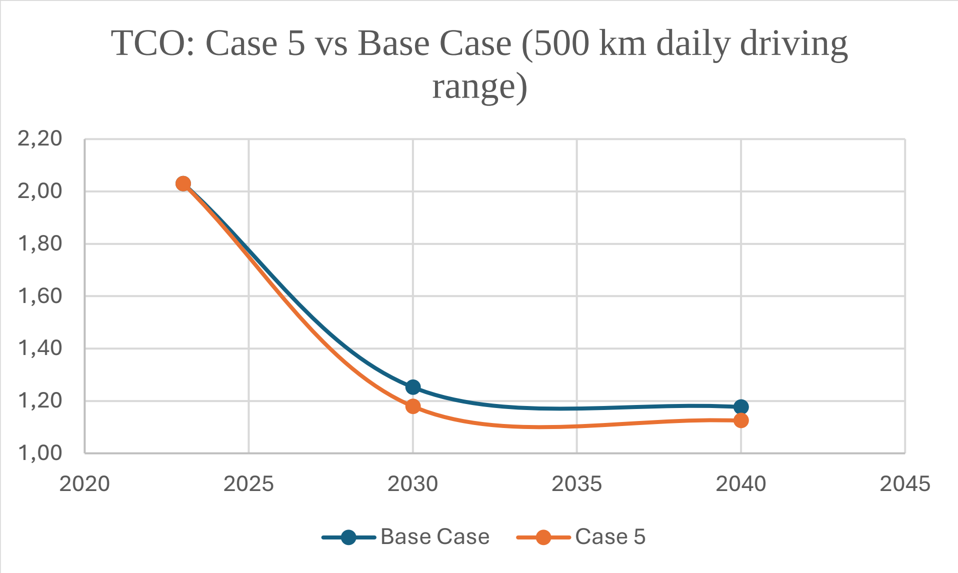

Figure 50. Comparison between the Base Case and Case 5 in terms of TCO for FCETs with a 500 km daily driving range in € for years 2023, 2030 and 2040.

As it is shown in *Table 189*, for *Case 5* the TCO for fuel cell electric trucks with a 500 km daily driving range is expected to change from 2.03 €/km in 2023 to 1.18 €/km for 2030 and to 1.12 €/km for 2040. These estimates are below the values computed for the *Base Case* for 2030 and 2040, as it can be seen in *Figure 50*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 5* for this daily driving range is approximately 5.8 % and 4.4 % lower than that of the *Base Case* for 2030 and 2040 respectively.

Additionally, for 2023 FCETs continue to have the highest TCO as the parameters for this year are the same as for the *Base Case*. However, for 2030 FECTs go from having the third highest TCO_1, being really close to diesel trucks in competitiveness, to being the third most competitive technology in terms of TCO_1. For this year, in terms of TCO_2 (CO_2 fees not being applied) FCETs continue to have the third highest TCO_2 as in the *Base Case*. Moreover, they continue to be the second most competitive technology for

2040 but get closer to BETs, which is the most competitive one for this year (there is around a 7 % difference between them).

For FCETs with an 800 km daily driving range, their TCO for years 2023, 2030 and 2040 for *Case 5* can be seen in *Table 190*. In addition to this, in *Figure 51* the comparison between the *Base Case* and *Case 5* in terms of TCO for this daily driving range is shown.

TCO considering the changing parameter (800 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	502.802	20.000	125.000	0,26	9,5%	5	245.473	158.349	1,85
	2030								
FCET	242.927	20.000	75.000	0,26	9,5%	5	154.905	158.349	1,04
	2040								
FCET	235.878	20.000	71.000	0,26	9,5%	5	141.647	158.349	0,97

Table 190. TCO for Case 5 for FCETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

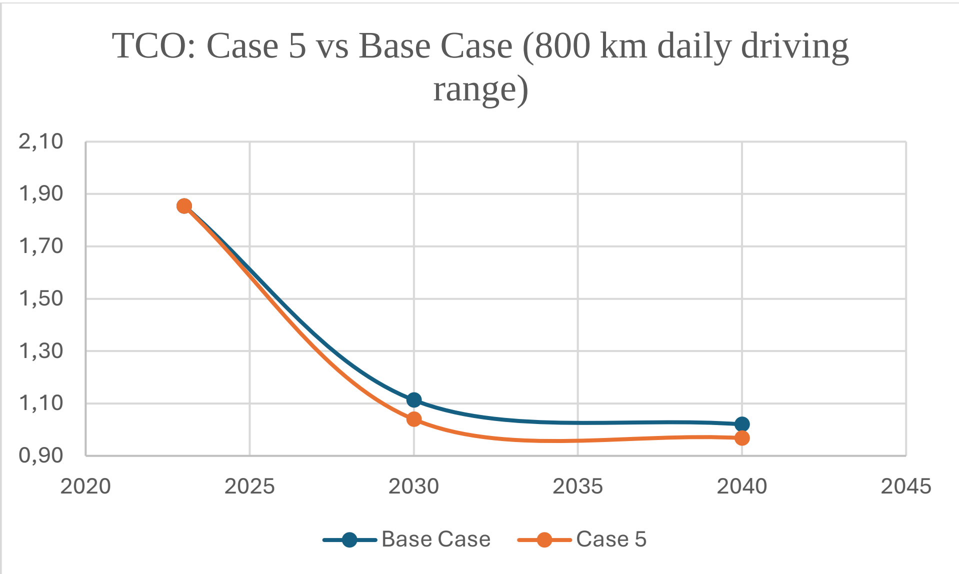

Figure 51. Comparison between the Base Case and Case 5 in terms of TCO for FCETs with an 800 km daily driving range in € for years 2023, 2030 and 2040.

As it can be observed in *Table 190*, for *Case 5* the TCO for fuel cell trucks with an 800 km daily driving range is expected to change from 1.85 €/km in 2023 to 1.04 €/km for 2030 and to 0.97 €/km for 2040. These estimates are lower than the values computed for the *Base Case* for 2030 and 2040, as it is shown in *Figure 51*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 5* for this daily driving range is around 6.6 % and 5.1 % lower than that of the *Base Case* for 2030 and 2040 respectively, which imply slightly higher decrements than those for trucks with a 500 km daily driving range.

Furthermore, for 2023 FCETs continue to have the highest TCO as the parameters for this year are the same as for the *Base Case*. In addition to this, for 2030 they stop having the third highest TCO_1 to become the third most competitive technology in terms of TCO_1 (CO_2 road charges considered). However, in terms of TCO_2 they continue to be the technology with the third highest TCO_2 for this year. Moreover, for 2040 FCETs continue to be the second most competitive technology, as in the Base Case, only below BETs with which the difference is of around 4.5 %.

When it comes to FCETs with a 1,000 km daily driving range, *Table 191* shows their TCO for years 2023, 2030 and 2040 for *Case 5*. Moreover, *Figure 52* displays the comparison between the *Base Case* and *Case 5* in terms of TCO for trucks with the previously mentioned daily driving range.

TCO considering the changing parameter (1000 km driving range) (€/km)									
	CAPEX	SUB	SV	CRF	i	N	OPEX 1 & 2	AKT	TCO 1 & 2
	2023								
FCET	525.033	20.000	98.000	0,26	9,5%	5	290.922	201.444	1,68
	2030								
FCET	258.933	20.000	79.000	0,26	9,5%	5	178.232	201.444	0,92
	2040								
FCET	246.516	20.000	74.000	0,26	9,5%	5	160.673	201.444	0,84

Table 191. TCO for Case 5 for FCETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

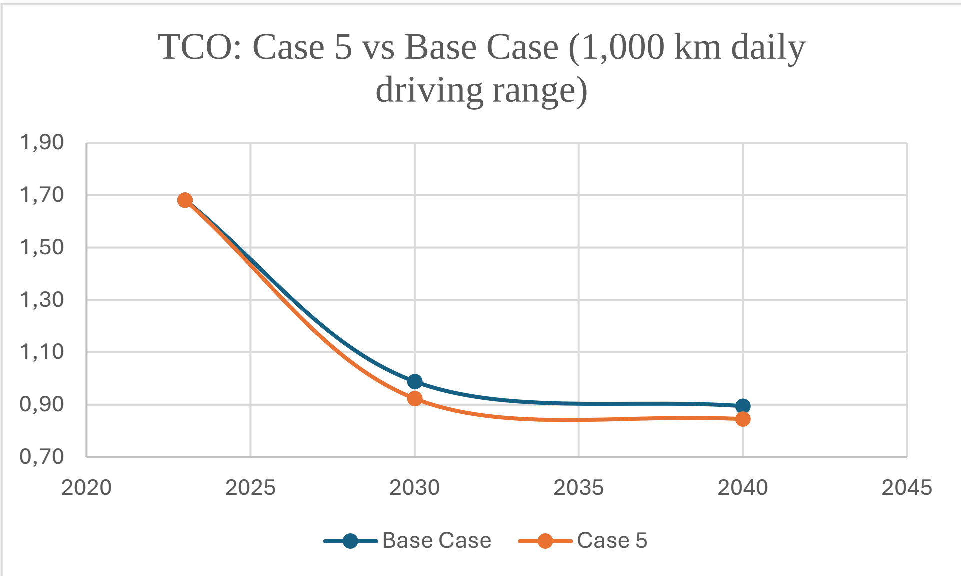

Figure 52. Comparison between the Base Case and Case 5 in terms of TCO for FCETs with a 1,000 km daily driving range in € for years 2023, 2030 and 2040.

As it can be seen in *Table 191*, for *Case 5* the TCO for fuel cell trucks with a 1,000 km daily driving range is expected to change from 1.68 €/km in 2023 to 0.92 €/km for 2030 and to 0.84 €/km for 2040. These estimates are below the values computed for the *Base*

Case for 2030 and 2040, as it is shown in *Figure 52*. Comparing the two cases in terms of TCO it can be calculated that the TCO of *Case 5* for this daily driving range is approximately 6.6 % and 5.6 % lower than that of the *Base Case* for 2030 and 2040 respectively. These decrements similar to the ones for trucks with an 800 km daily driving range but are higher than those for trucks with a 500 km daily driving range.

In addition to this, for 2023 FCETs continue to have the highest TCO as the parameters for this year are the same as for the *Base Case*. Moreover, for 2030 they become the most competitive technology in terms of TCO_1 by having a slightly lower TCO_1 than that of diesel trucks (around 0.1 % lower), which was the most competitive technology at the *Base Case*. Nevertheless, if CO_2 road charges are not considered for 2030 FCETs have the third lowest TCO_2 in contrast to the *Base Case* in which they had the third highest TCO_2. Furthermore, for year 2040 FCETs become the most competitive technology, surpassing diesel trucks, as it also happens at the *Base Case* (the difference between these two technologies in terms of TCO_1 and TCO_2 is larger for *Case 5*, of around 14.6 % and 9 % respectively).

CHAPTER 5. Discussion

After analysing the CAPEX, OPEX and TCO for diesel, HVO, e-diesel, fuel cell, battery electric and bio-CNG trucks in depth in the previous chapters for years 2023, 2030 and 2040 there are two key points that need to be considered to achieve a good and fast transition to zero-emission or at least less polluting technologies than diesel: energy dependence on third countries and refuelling infrastructure.

In Spain, there were 2,474,451 trucks registered in total for 2022, most of which were powered by diesel and less than 1 % by natural gas. This proves that alternative technologies for decarbonizing road freight have not yet successfully entered the Spanish market in terms of trucks. [11]

After the analysis made throughout *Chapter 4. Results,* it can be observed that for trucks with 500 km and 800 km daily driving ranges, BETs are the ones with the lowest TCO from 2030 onwards followed by diesel trucks for 2030 and by FCETS for 2040. Moreover, for trucks with 1,000 km daily driving ranges diesel and HVO trucks are the ones with the lowest TCO for 2030 yet for 2040 the lowest TCO corresponds to FCETs followed by that of diesel trucks. Nevertheless, the analysed points in this chapter -energy dependence and infrastructure- need to be taken into account as well, in addition to the TCO, when deciding which technology is the most convenient.

5.1. ENERGY VECTOR, SPANISH DEPENDENCE ON THIRD COUNTRIES AND ESTIMATED DEMAND FOR 2023, 2030 AND 2040

The analysis of Spain's dependence on third countries for 2023 regarding the energy and fuel needs for its road transport fleet will be focused on diesel and CNG trucks as these are the two most extended technologies for 2022: 99 % of the total freight is composed of diesel trucks followed by CNG trucks, which correspond to 0.22 % of the total freight. The remaining 0.78 % corresponds to other alternative technologies which are not stated. *Figure 53* shows the Spanish trucks' fleet for 2022. These 2022 values are assumed to be maintained for 2023. Additionally, it is assumed that all CNG trucks are powered by biomethane and therefore are bio-CNG. [11]

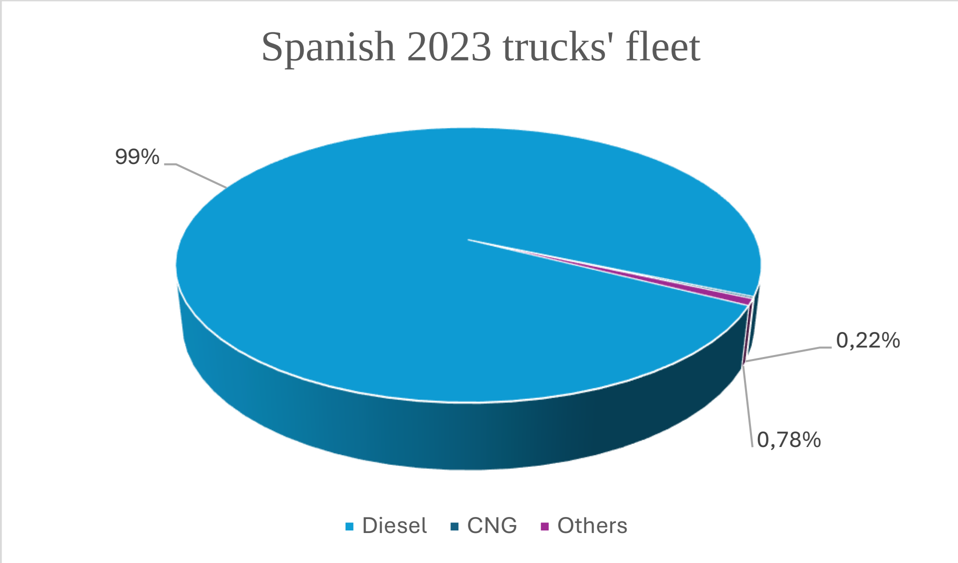

Figure 53. Spanish trucks' fleet for 2022 and 2023 for all daily driving ranges.

In Spain, diesel fuel is derived from a blend of crude oil and biodiesel. The biodiesel component is derived primarily from vegetable oils and is available in two distinct proportions: 7 % and 10 %. For 2023 it will be considered that diesel is made up of 8.5% of biodiesel. Additionally, it will be considered that biodiesel is produced in Spain or in other EU member states, while diesel comes from non-EU countries. [4], [21], [22]

In 2023, 99 % of the trucks ran on diesel, which translates into 2,449,706 trucks. On average, 54.5 % of these trucks belong to the 5-LH VECTO category studied in this report (1,335,090 trucks). Inside this category, there are 3 subcategories based on the different daily driving ranges (500 km, 800 km and 1,000 km). It will be assumed that 5-LH trucks are equally distributed among these subgroups. Considering this, as well as the annual travelled mileage and the trucks' fuel consumption, the total fuel consumption for 2023 was 65,450,212,165 litres, of which on average, 8.5 % (5,563,268,034 litres) were biodiesel (*Table 192*). As it can be seen, Spain has a strong dependence on other non-European countries when it comes to diesel as it needs to be imported in its totality. Nevertheless, the outlook for biodiesel is more promising. Europe currently has sufficient production capacity to meet its demand as the primary producer. [4], [5], [11], [12], [21], [22]

Expected biomethane consumption for 2023		
	CNG (kg)	CNG (GWh)
500 km	30.311.107,28	392,02
800 km	40.387.274,93	522,34
1000 km	52.295.083,64	676,35
Total	122.993.466	1.590,72

Table 192. Expected biomethane consumption from 5-LH trucks in Spain for 2023.

CNG trucks can work with natural gas, which Spain imports from non-EU countries, with biomethane (obtained from refined biogas through the "upgrading" process) or with a mixture of both. Biomethane is mainly composed of methane (between 92 % and 98 %) and has a density of around 0.75 kg/m_3. Additionally, 1 m^3 of CH_4 produces around 10 kWh in the same conditions of pressure and temperature as those of the biomethane density provided. Considering that methane is the main source of energy for biomethane and that the produced biomethane in Spain in general has around 97 % of CH_4, it can be deduced that 1 kg of biomethane produces around 12.93 kWh. [20], [58], [59]

For 2023, only 0.22 % of the total number of trucks worked with CNG in Spain (5,419 trucks), of which, on average, 54.5 % belong to the 5-LH VECTO category (2,967 trucks). It is assumed that all of them are powered by biomethane. Inside this category, there are 3 subcategories based on the different daily driving ranges (500 km, 800 km and 1,000 km). It is assumed that 5-LH trucks are equally distributed among these subgroups. Considering calculations from the previous paragraph as well as the engine consumption and the annual travelled mileage, the total biomethane consumption for 2023 was 122,993,466 kg of biomethane, which provide 1,590.72 GWh (*Table 193*). [4], [5], [11], [20], [58], [59]

Expected diesel and biodiesel consumption for 2023		
	Diesel	Biodiesel
500 km	14.908.730.410	1.384.964.027
800 km	19.795.441.486	1.838.920.794
1000 km	25.182.772.235	2.339.383.213
Total	59.886.944.131	5.563.268.034

Table 193. Expected diesel and biodiesel consumption from 5-LH trucks in Spain for 2023.

In Spain, there are currently 8 commercial plants capable of producing 349 GWh/year of biomethane and 13 pilot plants with a capacity production of 22.86 GWh/year, which is intended to nurture the transport sector. The obtained biomethane is only partially aimed at supplying the transport sector demand. Therefore, this production is not enough to supply the total biomethane demand for CNG trucks, so Spain would be partially dependent on European member states such as Germany or France, which are one of the main European producers. [11]

To analyse Spain's dependence on third countries for 2030 and 2040, it is assumed that the Spanish road freight is composed of the same number of trucks as for 2023 and that the share of 5-LH trucks will be the same (54.5 %). Moreover, it will also be assumed that 5-LH trucks are equally distributed among the three established subcategories based on the daily driving range (500 km, 800 km and 1,000 km) as it was done for 2023. Nevertheless, the proportion in which the different technologies are found among the total number of trucks will vary depending on the year, considering the analysis done in *Chapter 4. Results* for the different daily driving ranges.

For 2030, focusing on trucks with 500 km and 800 km daily driving ranges, the lowest TCO is that of BETs, followed by diesel and HVO trucks. Fuel cell, e-diesel and CNG trucks are not considered competitive for this year. However, an increase in CNG trucks will be considered because in 2023 there were trucks with this technology and back then they were competitive in terms of TCO. Therefore, it is reasonable to expect that there are still CNG trucks registered. E-diesel and fuel cell trucks are not expected to be part of the truck's fleet for this year as they are far from the most competitive technologies and in 2023 they were not competitive either, so it is estimated that no registrations of trucks with these technologies will be done between 2023 and 2030.

The trucks' fleet is assumed to be distributed like this for trucks with 500 km and 800 km daily driving ranges in 2030: 75 % diesel trucks (337,144 trucks for each daily driving range), 15 % BETs (67,429 trucks for each daily driving range), 8 % HVO trucks (35,962 trucks for each daily driving range) and 2 % bio-CNG trucks (8,991 trucks for each daily driving range). For these technologies it is assumed that their fuel consumption is the same as the one selected for the *Base Case* for year 2030. Moreover, it will be considered that the percentage of biodiesel in the diesel mixture will increase from 8.5 % in 2023 to 10 % in 2030.

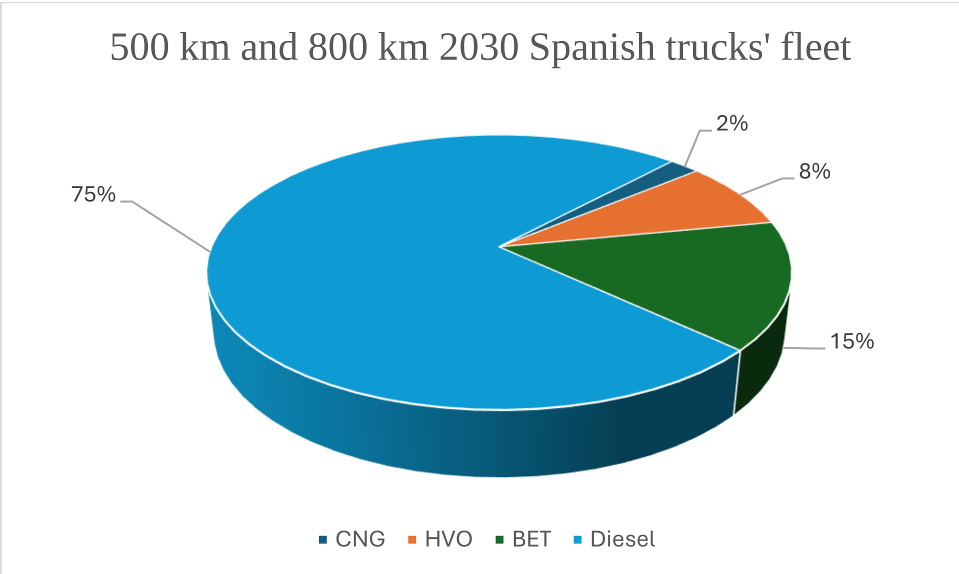

Figure 54. Spanish 5-LH trucks' fleet for 500 km and 800 km daily driving range trucks for 2030.

For trucks with 500 km daily driving ranges, this implies the following annual fuel consumptions: 216,167,509 kg of biomethane (2,795.77 GWh), 995,001,449 litres of HVO, 7,719.87 GWh for BETs and 9,328,145,504 litres of diesel of which 932,814,550 litres are biodiesel.

Additionally, for trucks with 800 km daily driving ranges this implies the following annual fuel consumptions: 289,726,909 kg of biomethane (3,747.13 GWh), 1,321,138,180 litres of HVO, 10,357.02 GWh for BETs and 12,385,679,626 litres of diesel of which 1,238,567,963 litres is biodiesel.

Regarding trucks with 1,000 km daily driving ranges for 2030, the lowest TCO is that of diesel trucks followed by HVO and battery electric trucks. Fuel cell, e-diesel and CNG trucks fully running on biomethane are not considered competitive for this year. However, an increase in CNG trucks will be considered because in 2023 there were trucks with this technology and back then they were competitive in terms of TCO. Therefore, it is reasonable to expect that there will still be CNG trucks registered for years close to 2023.

E-diesel and fuel cell trucks are not expected to be part of the truck's fleet for this year as they are far from the most competitive technologies and in the year 2023 they were not competitive either, so no registrations of trucks with these technologies are expected between 2023 and 2030.

The trucks' fleet is assumed to be distributed like this for trucks with 1,000 km daily driving ranges in 2030: 85 % diesel trucks (382.096 trucks), 8 % HVO trucks (35,962 trucks), 5 % BETs (22,476 trucks) and 2 % CNG trucks (8,991 trucks). For these technologies, it will be assumed that their fuel consumption is the same as the one selected for the *Base Case* in 2030. Moreover, it will be considered that the percentage of biodiesel in the diesel mixture will increase from 8.5 % in 2023 to 10 % in 2030.

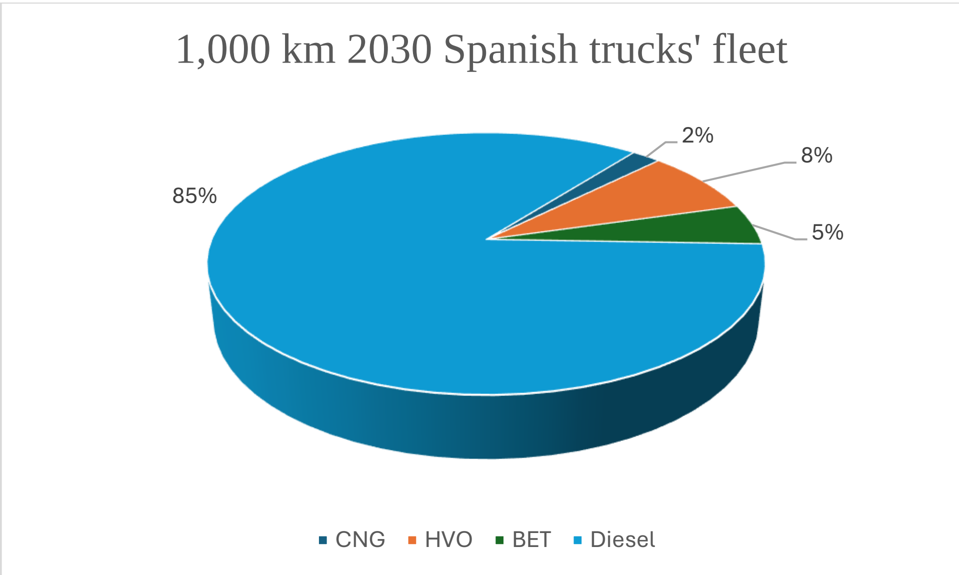

Figure 55. Spanish 5-LH trucks' fleet for 1,000 km daily driving range trucks for 2030.

Furthermore, for trucks with 1,000 km daily driving ranges, this implies the following annual fuel consumptions: 374,190,780 kg of biomethane (4,839.53 GWh), 1,680,686,026 litres of HVO, 4,505.02 GWh for BETs and 17,857,277,346 litres of diesel of which 1,785,727,735 litres is biodiesel.

The total quantities needed of each fuel for year 2030 considering the whole 5-LH trucks' fleet for the previously explained hypothetical scenario would be: 880,085,198 kg of biomethane (11,382.44 GWh), 3,996,825,656 litres of HVO, 22,581.91 GWh for BETs and 39,571,102,477 litres of diesel of which 3,957,110,248 litres is biodiesel (see *Table 194*).

Expected fuel consumption for 2030						
	CNG (kg)	**CNG (GWh)**	**HVO (litres)**	**BET (GWh)**	**Diesel (litres)**	**Biodiesel (litres)**
500 km	216.167.509	2.795,77	995.001.449	7.719,87	9.328.145.504	932.814.550
800 km	289.726.909	3.747,13	1.321.138.180	10.357,02	12.385.679.626	1.238.567.963
1000 km	374.190.780	4.839,53	1.680.686.026	4.505,02	17.857.277.346	1.785.727.735
Total	880.085.198	11.382,44	3.996.825.656	22.581,91	39.571.102.477	3.957.110.248

Table 194. Expected fuel consumption from 5-LH trucks in Spain for 2030.

In terms of biomethane, in 2022 Spain had 8 plants with a production capacity of 349 GWh/year 13 pilot plants with a capacity production of 22.86 GWh/year. This is expected to increase for the next decade as the Spanish government is encouraging the creation of new biomethane production plans through subsidies. Therefore, it may be reasonable to think that of the total 2030 biomethane Spanish demand for trucks, Spain could be able to supply between a quarter and a third of it. The remaining part could be imported from EU member states such as Germany, one of the main producers. [11]

When it comes to HVO, for 2021, Spain had 7 HVO production plants owned by companies such as CEPSA, Repsol and BP with a total production of around 0.75 annual million metric tons. Considering that HVO density is, on average, approximately 778 kg/m^3 at 15ºC, the total annual Spanish capacity was 964,010,283 litres for 2021 which is around 24.1 % of the 2030 demand. Considering that HVO trucks are a competitive technology for 2030 and 2040, especially for trucks with high daily driving ranges, it is likely that companies as well as the Spanish government, will encourage HVO production plants as it can lower by up to 90 % well-to-wheel CO_2 emissions. Additionally, if there is part of the HVO demand that Spain cannot cover, imports from European countries such as the Netherlands, Italy, France, Finland or Sweden could be made as these countries have higher production capacities than that of Spain for 2021 and it is likely that it increases for 2030. [13], [14]

Diesel needs to be imported from third countries that do not belong to the European Union. However, the EU was the largest biodiesel productor for the previous years, annually producing around 15,000,000,000 litres of biodiesel for years from 2020 to 2023. Actually, for 2030 this quantity is significantly expected to increase to speed up the ecological transition. The Spanish biodiesel demand for 2030 is close to being 26.4 % of the annual biodiesel produced for 2023 within the EU. Considering the previously mentioned increase in production, it is expected that Spain only depends on itself and on third European countries to satisfy the 2030 biodiesel demand. [12]

Based on the Spanish *Plan Nacional Integrado de Energía y Clima* (PNIEC) for the 2021-2030 period, the 2030 target is a 23 % reduction in the GHGs emissions compared to that of 1990. Considering this, for 2030, out of the total electricity production, around a 73.4 % should come from renewable sources. However, based on the current tendency, it is likely that for 2030, only about 51.6 % of the electricity produced comes from these sources. [15]

This implies that out of the 22,581.91 GWh demanded by BETs for 2030, 11,652.27 GWh would come from renewable sources, whereas 10,929.64 GWh would come from non-renewable ones for the hypothetical 2030 suggested scenario. Moreover, it can be considered that Spain does not depend on third countries when it comes to renewable energy sources, while for non-renewable ones, importations of mainly nuclear fuel, natural gas and coal are needed for 2030. This leads to Spain being dependent on third countries which may or may not belong to the EU for supplying 48.4 % of the BETs demand. [15], [16]

For 2040, when it comes to trucks with 500 km and 800 km daily driving ranges, the lowest TCO is that of battery electric trucks followed by fuel cell and diesel trucks. As a result, this year's total diesel truck share is expected to decrease. Moreover, HVO, e-diesel, and CNG trucks that are fully running on biomethane are not considered competitive this year. However, a small increase in HVO trucks will be considered because in 2030 there were trucks with this technology and back then they were competitive in terms of TCO. Therefore, it is reasonable to expect that there will still be HVO trucks registered for years close to 2030.

In addition to this, the number of CNG trucks will be assumed to decrease as from 2030 onwards they are not competitive in terms of TCO and therefore no more registrations of this type of trucks are expected between 2030 and 2040. Finally, e-diesel trucks are not expected to be part of the truck's fleet for this year as they are far from the most competitive technologies and in the year 2023 they were not competitive either, so no registrations of trucks with these technologies are expected between 2023 and 2030.

The trucks' fleet is assumed to be distributed like this for trucks with 500 km and 800 km daily driving ranges in 2030: 50 % diesel trucks (224,763 trucks for each daily driving range), 30 % BETs (134,858 trucks for each daily driving range), 14.7 % FCETs (66,080 trucks for each daily driving range), 5 % HVO trucks (22,476 trucks for each daily driving range) and 0.3 % CNG trucks (1,349 trucks for each daily driving range). For these technologies, it will be assumed that their fuel consumption is the same as the one selected for the *Base Case* for year 2040. Moreover, the percentage of biodiesel in the diesel mixture will be 10 %, as it has been assumed for 2030.

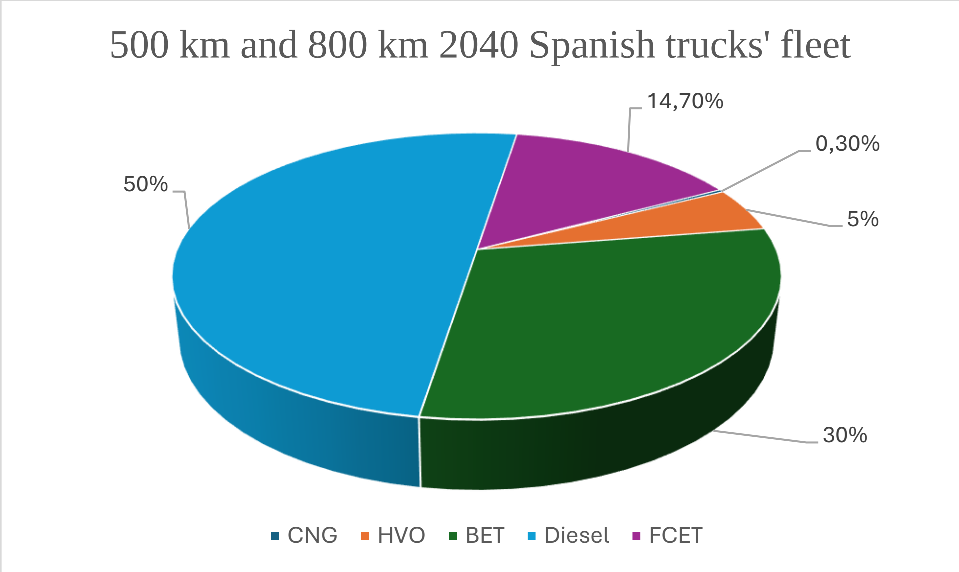

Figure 56. Spanish 5-LH trucks' fleet for 500 km and 800 km daily driving range trucks for 2040.

For trucks with 500 km daily driving ranges this implies the following annual fuel consumptions: 32,433,541 kg of biomethane (419.47 GWh), 15,439.73 GWh for BETs, 458,653,710 kg of hydrogen, 621,868,989 litres of HVO, and 6,218,772,892 litres of diesel of which 621,877,289 litres is biodiesel.

Additionally, for trucks with 800 km daily driving ranges, this implies the following annual fuel consumptions: 43,470,315 kg of biomethane (562.22 GWh), 825,702,179 litres of HVO, 20,714.04 GWh for BETs and 8,257,131,997 litres of diesel of which 825,713,200 litres is biodiesel.

Talking about trucks with 1,000 km daily driving ranges for 2040, the lowest TCO is that of fuel cell trucks, followed by diesel and HVO if CO_2 road charges are not applied, or diesel and battery electric trucks if considering CO_2 road fees. CNG and e-diesel trucks are not considered competitive for this year. Therefore, e-diesel trucks are not expected to be part of the truck's fleet for 2040 as they are far from the most competitive technologies and in the previous decades, they were not competitive either, so no registrations of these trucks are considered during the 2023-2040 period.

Additionally, the number of CNG trucks will be assumed to decrease as from 2030 onwards, they are not competitive in terms of TCO, and therefore, no more registrations of this type of trucks are expected between 2030 and 2040. Moreover, as HVO may be the third most competitive technology, it will be assumed that its share increases compared to that of 2030. The share of diesel is expected to decrease slightly as FCETs, which are more competitive, are expected to start appearing as part of the trucks' fleet. Finally, BETs stop being as competitive as they were for 2030, so a small decrement is assumed for this technology.

The trucks' fleet is assumed to be distributed like this for trucks with 1,000 km daily driving ranges in 2030: 77 % diesel trucks (346,134 trucks), 10 % HVO trucks (44,953 trucks), 3 % BETs (13,486 trucks), 0.3 % CNG trucks (1,349 trucks) and 9.7 % for FCETs (43,604 trucks). For these technologies, it will be assumed that their fuel consumption is the same as the one selected for the *Base Case* for year 2040. Moreover, it will be considered that the percentage of biodiesel in the diesel mixture will increase from 8.5 % in 2023 to 10 %, as it happened in 2030.

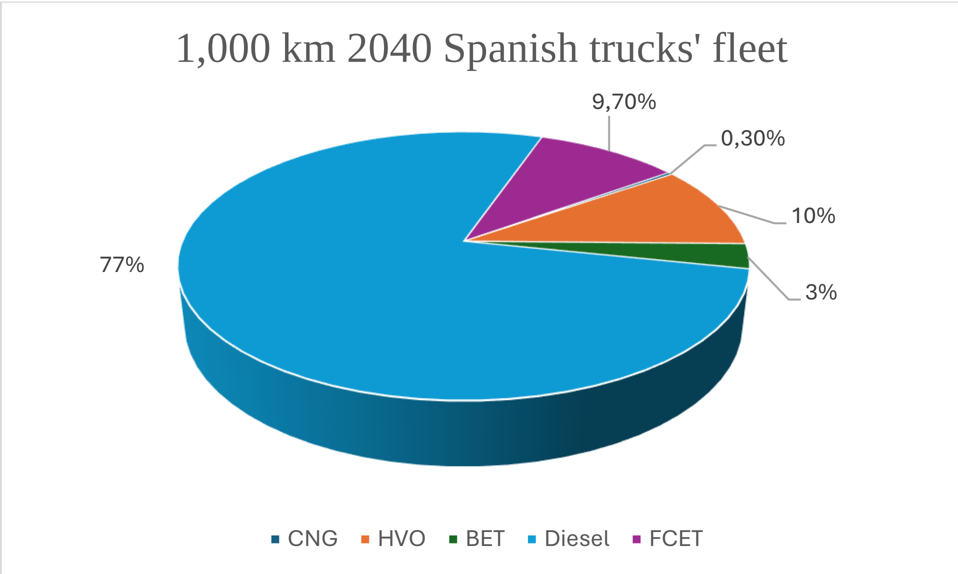

Figure 57. Spanish 5-LH trucks' fleet for 1,000 km daily driving range trucks for 2040.

As it can be observed in the previous paragraph, the hypothetical trucks' fleet distribution based on the different existing technologies for trucks with 1,000 km daily driving ranges is more conservative than those for the previously studied daily driving ranges for 2040 in terms of the entrance of zero-emission technologies and their share. This is because, for 2023 and 2030, battery electric and fuel cell trucks will not be as competitive. On the contrary, the most competitive technologies for this driving range until 2040 are diesel and HVO.

Furthermore, for trucks with 1,000 km daily driving ranges, this implies the following annual fuel consumptions: 56,143,183 kg of biomethane (726.12 GWh), 2,100,880,900 litres of HVO, 2,703.09 GWh for BETs, 516,485,846kg of hydrogen and 16,176,591,320 litres of diesel of which 1,617,659,132 litres are biodiesel.

The total quantities needed of each fuel for year 2040, considering the whole trucks' fleet for the previously explained hypothetical scenario, would be: 132,047,039 kg of biomethane (1,707.81 GWh), 3,548,452,068 litres of HVO, 38,856.87 GWh for BETs, 1,587,267,665 kg of hydrogen and 30,652,496,208 litres of diesel of which 3,065,249,621 litres is biodiesel (see *Table 195*).

Expected fuel consumption for 2040							
	CNG (kg)	CNG (GWh)	HVO (litres)	BET (GWh)	FCET (kg)	Diesel (litres)	Biodiesel (litres)
500 km	32.433.541	419,47	621.868.988,77	15.439,73	458.653.710	6.218.772.892	621.877.289
800 km	43.470.315	562,22	825.702.178,54	20.714,04	612.128.109	8.257.131.997	825.713.200
1000 km	56.143.183	726,12	2.100.880.900,44	2.703,09	516.485.846	16.176.591.320	1.617.659.132
Total	132.047.039	1.707,81	3.548.452.068	38.856,87	1.587.267.665	30.652.496.208	3.065.249.621

Table 195. Expected fuel consumption from 5-LH trucks in Spain for 2040.

In terms of biomethane, for 2040 the demand within the truck sector is expected to be 1,707.81 GWh for the proposed scenario. This could be partially covered by the current Spanish biomethane infrastructure (Spain 8 plants with a production capacity of 349 GWh/year and 13 pilot plants with a capacity production of 22.86 GWh/year for 2022). Actually, the biomethane production capacity is expected to notably increase between 2023 and 2040, so even if not all the produced biomethane for 2040 is destined for the heavy transport sector. It could be reasonable to think that Spain will be able to cover at least half of this demand with its internal biomethane production for 2040. Nevertheless, the non-supplied demand could be imported from European countries, which are expected to increase their biomethane production capacity for the next decades as well. [11]

Regarding HVO, for 2021, there were 7 HVO production plants in Spain with a total production capacity of 0.75 annual metric tons. Considering that HVO density is, on average, around 778 kg/m^3 at 15ºC, the total annual Spanish capacity was 964,010,283 litres for 2021, which is around 27.2 % of the 2040 demand. Additionally, as HVO trucks are competitive for 2030 and 2040, especially for trucks with high daily driving ranges, it could be expected that companies and the Spanish government will encourage HVO production plants as this technology can reduce up to 90 % of well-to-wheel CO_2 emissions. Moreover, if Spain did not have enough production capacity, HVO could be imported from other European countries like the Netherlands, France or Sweden among others as they have a high production capacity that is expected to increase throughout the 2023-2040 period. [13], [14]

In contrast to the previous fuels, diesel needs to be imported from third countries that do not belong to the European Union. Nevertheless, the EU was the largest biodiesel producer for the previous years, annually producing around 15,000,000,000 litres of biodiesel for years from 2020 to 2023. In addition to this, it is expected that during the 2023-2040 period the production capacity of biodiesel within the EU borders skyrockets for speeding up the ecological transition. The Spanish biodiesel demand for 2040 is approximately 20.4 % of the European production capacity for 2023. Considering the previously mentioned increase in production, Spain is expected to only depend on itself and maybe on third European countries to satisfy the 2040 biodiesel demand. [12]

Focussing on hydrogen for FCETs, for year 2040 the expected total demand is of 1,587,267,665 kg. For 2021, Spain had a green hydrogen production capacity of 600,000,000 kg per year, which is around 37.8 % of the expected demand for 2040. Moreover, this production capacity is expected to increase for the following decades -

based on the National Hydrogen Roadmap the total electrolyser Spanish capacity will increase to 600 MW by 2024 and to 4 GW by 2030-. However, it is necessary to consider that not all of the hydrogen produced is destined to supply the heavy-duty demand. Despite this, the non-supplied hydrogen demand from this sector could be satisfied by importing green hydrogen from other European countries. If these imports are not enough, another alternative could be to import the remaining parts from countries such as Egypt or Brazil, which produce green hydrogen as well. [4], [17]

When it comes to electricity production for BETs, the Spanish *Plan Nacional Integrado de Energía y Clima* (PNIEC) for the 2021-2030 period establishes a 23 % reduction of GHGs compared to 1990 for the year 2030. To achieve this objective, 73.4 % of the produced electricity should come from renewable sources. Nevertheless, based on the current tendency, it could be estimated that by 2030, only about 51.6 % of the produced electricity will come from these sources. [15]

Therefore, for the proposed 2040 scenario to analyse the Spanish energetic independence in terms of heavy-duty trucks, it will be considered that 80 % of the electricity produced will come from renewable energy sources. This a reasonable `prediction considering that important Spanish electricity generators have a strong compromise with producing electricity by using renewable energy sources as well as achieving net zero emissions. [18], [19]

Considering this, it can be computed that out of the 38,856.87 GWh demanded by BETs for 2040, 31,085.50 GWh would come from renewable sources, whereas 7,771.37 GWh would come from non-renewable ones for the hypothetical 2040 proposed scenario. Moreover, it can be considered that Spain does not depend on third countries when it comes to renewable energy sources, whereas for non-renewable ones, imports of mainly nuclear fuel and natural gas are required -it has been assumed that coal thermal powerplants will completely disappear for 2040 in Spain-. This leads to Spain's dependence on third countries that may or may not belong to the EU for supplying 20 % of the BETs demand. [15], [16]

5.2. GUIDELINE OF THE REFUELLING INFRASTRUCTURE

In 2023, there were a total of 131 gas stations in Spain which could provide CNG and 33 new planned stations. According to the Alternative Fuels Infrastructure Deployment (AFID), the supply points for CNG at the TEN-T network should be located at a maximum distance of 150 km. Currently, there is a new European Directive substituting the AFID one, which is the AFIR (Alternative Fuels Infrastructure Regulation) in which there are no new objectives established for CNG stations as it is considered that the existing European network is reliable enough. Considering the number and placement of the CNG station in Spain, the AFIR and the AFID European Directives are accomplished, as there are 31 % more CNG stations than that required to fulfil it. [11]

On the contrary, in 2023, there were only 9 hydrogen stations operating in Spain. Moreover, only 2 of them are of public access and most of them provide hydrogen at 350 bar and have a maximum supply capacity of 100 kg/day. All of this shows that Spain is far from the objectives settled in the European legislation -between 100 and 150 hydrogen stations should be deployed by 2030. According to the AFIR legislation, by 2030, there should be a minimum of one hydrogen station every 200 km in the TEN-T network with the capacity of providing a minimum 1 tone of hydrogen per day at 700 bar. Additionally, there should be one hydrogen station of these characteristic at every urban core. [11], [23]

Moreover, in Spain for 2023 there were around 100 renewable hydrogen production projects in preliminary stages. If developed, the accumulated electrolysis power would increase to 18.1 GW and a third of the production would be intended for the transportation sector. [11]

When it comes to the Spanish battery recharging points, in the second quarter of 2024, there were 7,515 DC and 22,886 AC recharging points, according to the AFIR classification. Moreover, the DC recharging points can be divided into slow ($P < 50$ kW), fast (50 kW $\leq P <$ 150 kW), Level-1 ultra-fast (150 kW $\leq P <$ 350 kW) and Level-2 ultra-fast ($P \geq$ 350 kW) according to the AFIR classification. In May 2024, there were 509 slow, 4,388 fast, 2,201 Level-1 ultra-fast and 417 Level-2 ultra-fast DC recharging points. [24]

Additionally, the AC charging points are categorized by the AFIR as slow ($P < 7.4$ kW), medium-speed (7.4 kW $\leq P \leq$ 22 kW) and fast ($P >$ 22 kW). In May 2024, there were 1,418 slow, 19,912 medium-speed and 1,556 fast AC recharging points. [24]

The AFIR Directive also establishes new infrastructure requirements for charging stations that Spain will need to achieve for 2025 and 2030. For example, it is stated that for heavy-duty vehicles, charging stations should have a minimum available power of 350 kW and that they should be placed at a maximum distance of 60 km for the core TEN-T network and 100 km on the broader TEN-T global network for 2025. In addition to this, it is claimed that the road network must have full coverage by 2030. In Spain, the AFIR map shows that currently there are sections of highways in the TEN-T network that meet these charger/km requirements, but there are still several of them that do not comply. [23], [25]

Talking about diesel fuels containing biodiesel the infrastructure is already fully developed. Additionally, for HVO trucks, which is a technology that has been estimated that will be competitive during the 2023-2040 period, they could refill their deposits at traditional petrol stations as the same refuelling mechanism is used and the range of densities of this fuel and that of diesel and gasoline are similar. The only requirement for conventional petrol stations to supply HVO is for them to have it in stock. Therefore, they could either enlarge some of the existing gas stations located on strategic points or partially substitute the diesel and gasoline tanks they have at some stations for HVO tanks, which actually is reasonable as for the next decades, the diesel and gasoline demand for road transport is expected to decrease due to the entrance of new technologies.

CHAPTER 6. Conclusions

Currently one of the most important and difficult challenges that our society is facing is reducing transport emissions. Aligned with this major objective this final degree project has as main goals the following:

- Characterize technological alternatives for achieving zero emissions in road freight transport carried out by trucks. Technological and economic characteristics will be provided for the different current and alternative technologies (*Chapters 2, 3 and 4*).
- Establish the energetic vector for each of the previously mentioned technologies and whether Spain would be dependent on third countries based on the different energy sources (*Chapter 5*).
- Quantify the demand and estimate the required infrastructure as a guideline based on different scenarios (*Chapter 5*).

In this project the CAPEX, OPEX and TCO of diesel, e-diesel, HVO, bio-CNG, battery and fuel cell trucks has been computed and analysed for 2023, 2030 and 2040, as well as the Spanish level of dependency on third countries for supplying the Spanish trucks' fleet fuel demand and the available and expected refuelling infrastructures to determine the viability of the different technologies. The main obtained conclusions are the following:

<u>Regarding the CAPEX</u>

- For 2023 FCETs and BETs have the highest CAPEXs, and there is a large gap between them and the retail price of the rest of technologies. However, they are expected to be the technologies with the highest CAPEX reduction for throughout the 2023-2040 period (around 50%).
- Estimated significant retail price reductions of the energy battery -for BETs- and of the fuel cell system -for FCETs- during the 2023-2040 period is mainly what causes these technologies to be more competitive and considerably less affected by inflation for 2030 and 2040.
- Despite this, in 2040 diesel, HVO and e-diesel trucks continue to have the lowest CAPEX for high daily driving ranges (800 km and 1,000 km) due to the large energy battery and the fuel cell sizes they require to be viable. On the contrary, BETs have the lowest CAPEX for 2040 for 500 km daily driving range trucks.
- CNG, diesel, e-diesel and HVO trucks' CAPEXs are expected to increase from 2023 to 2040 mainly due to inflation, as they are considered mature, and therefore, fully developed technologies.

In terms of OPEX and TCO

- For 500 km and 800 km daily driving ranges BETs have the most competitive OPEX during the studied period mainly due to their efficiency and low charging costs as it is considered that they charge 80 % of the times in their deposits.
- However, for 1,000 daily driving range trucks BETs are not as competitive because it is assumed that they mostly charge in public stations, which is considerably more expensive because of higher power charging infrastructure.
- In terms of OPEX and TCO, the best option in the long term to substitute diesel trucks with 1,000 km daily driving ranges is that of FCETs.

Competitiveness in 2030 and 2040

- Bio-CNG and e-diesel trucks are competitive in terms of TCO for 2023 because of their low CAPEXs. However, from 2030 onwards they stop being competitive because their OPEXs continue to be high compared to the rest of technologies. Another reason is that their CAPEXs increase as those of the other mature technologies while FCETs and BETs experience significant CAPEXs reductions.
- It is likely that for 2030 most of the 5-LH trucks are diesel, battery electric or HVO, while for 2040 chances are that the weight of BETs and FCETs considerably increases depending on the daily driving range.
- For 500 km and 800 km daily driving ranges, for 2030 there are TCOs lower than that of diesel (even when considering CO_2 road fees), whereas for 1,000 km daily driving ranges diesel has the lowest TCOs until 2040.

Regarding the sensitivity analyses

- Selecting the most optimistic values for BETs' energy batteries, makes BETs even more competitive for 2030 and 2040 for 500 km and 800 km daily driving ranges despite already having the lowest TCO. However, for 1,000 km trucks this optimistic prediction only lowers BETs' TCO enough for them to become the second most competitive technology in 2040 if CO_2 fees are applied, being FCETs the most competitive.
- Optimism in the reduction of the fuel cell system retail price is not enough for FCETs to be better positioned on the TCO rankings except for 1,000 km FCETs, which become the third most competitive technology for 2030.
- For 2040, a diesel retail price of 1,75 €/l excluding VAT implies that BETs, FCETs and HVO become the most competitive technologies.
- Considering a 25 % and a 50 % decrease in the electricity price for 2030 and 2040 compared to that of 2023, BETs become the most competitive technology in terms of TCO for all daily driving ranges for 2040.
- A 20 % decrease in the at-the-pump hydrogen retail price does not imply any changes in the TCOs 2040 rankings for FCETs.

Spanish 2023 fuel dependency on third countries

- For 2023 Spain heavily depends on third non-EU countries for importing crude oil while being partially dependent on EU countries for covering the biodiesel and biomethane expected demand.

Spanish 2030 fuel demand and dependency on third countries

- The expected 2030 fuel demand is of around 11.4 thousand GWh from biomethane, around 4 billion litres of HVO, 22.6 thousand GWh from electricity and 39.57 billion litres of diesel of which 3.96 billion litres are biodiesel (10 %).
- For 2030 Spain is expected to cover around a quarter of the biomethane demand and at least 24.1 % and 26.4 % of the HVO and the biodiesel demand respectively, probably relying only on other EU countries to cover the remaining part. Moreover, 51.6 % of the total electricity demand is expected to be produced by renewable energy sources, so Spain would only depend on EU and non-EU counties for 48.4 % of the required electricity. Additionally, crude oil is fully imported from third non-EU member states.

Spanish 2040 fuel demand and dependency on third countries

- The expected 2040 fuel demand is of around 1.71 thousand GWh from biomethane, 3,55 billion litres of HVO, 38.86 thousand GWh from electricity, 1,6 billion kg of hydrogen and 30,65 billion litres of diesel of which 3,07 litres are biodiesel (10 %).
- For 2040 Spain is expected to be able to cover about half of the biomethane demand and at least 27.2 %, 20.4 % and 37.8 % of the HVO, biodiesel and hydrogen demands respectively, being the remaining demand supplied by EU countries or countries such as Brazil or Egypt when it comes to green hydrogen. Furthermore, around 80 % of the required electricity is expected to be produced by renewable energy sources for 2040. Finally, crude oil needs to be imported from third non-EU member states.

Spanish refuelling infrastructure

- The Spanish gas stations network complies with the AFIR regulation, so the refuelling infrastructure would not limit the adoption of this technology.
- Spain is currently far from complying with the AFIR regulation in terms of hydrogen stations and chances are that it will not accomplish it by 2030 either, which makes it unlikely for FCETs to increase their market share before 2040 due to the lack of refuelling infrastructure.
- Despite the increase in chargers of a minimum available power of 350 kW, most of the Spanish TEN-T network do not cover the AFIR regulation now. However, for 2030 Spain could manage to comply with this regulation.

ANNEX 1. Sustainable Development Goals

The 17 Sustainable Development Goals (SDG) are the heart of the 2030 Agenda for Sustainable Development, which was adopted by all United Nations Member States in 2015 and whose purpose is to ensure peace and prosperity now and in the long term for people and the planet. *Figure 4* shows the 17 SDG. [60]

Figure 4: Sustainable development goals. [60]

This project is closely related to the SDGs previously mentioned as it studies zero-emission technologies in road freight transport. Examples of this project alignment with the SDGs are the following:

- SGD-03: "Good health and well-being: ensure healthy lives and promote well-being for all at all ages". This Objective is closely linked to the transport sector, as implementing technological alternatives in order to reduce emissions of harmful pollutants would reduce the number of annual premature deaths.
- SGD-07: "Affordable and clean energy: ensure access to affordable, reliable, sustainable and modern energy for all". This Objective directly affects the freight transport sector as most of the operating means of transportation use fossil fuels.
- SGD-09: "Industry, innovation and infrastructure: build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". In order for the freight transport sector to transition to being zero-emission the buildup of new infrastructure such hydrogen stations are going to be required. Moreover, it will also have an impact on the electrical network depending on the demand.
- SGD-12: "Responsible consumption and production". Road freight transport is a key part of many supply chains, especially in the EU. Therefore, to achieve a responsible consumption this stage of the supply chain needs to be sustainable and decarbonized.

Additionally, the same is required for achieving responsible production, as road freight transport is used for carrying raw materials to the factories.

- SGD-13: "Climate action: take urgent action to combat climate change and its impact". This Objective is particularly related to the road freight transport sector, which is currently responsible for a relevant percentage of the GHGs total emissions.

ANNEX 2. Truck's retail prices assumed for calculating the insurance and the scrappage value

5-LH (500 km) truck's retail price (€)			
	2023	2030	2040
Diesel	152.000	167.000	167.000
HVO	152.000	167.000	167.000
BET	354.000	181.000	159.000
Bio-CNG	159.000	169.000	168.000
e-Diesel	152.000	167.000	167.000
FCET	486.000	195.000	175.000

Annex 2. Table 1. Retail price for 5-LH trucks with a daily driving range of 500 km based on its technology for years 2023, 2030 and 2040 in €. [4]

5-LH (800 km) truck's retail price (€)			
	2023	2030	2040
Diesel	176.000	192.000	192.000
HVO	176.000	192.000	192.000
BET	457.000	222.000	202.000
Bio-CNG	188.000	199.000	198.000
e-Diesel	176.000	192.000	192.000
FCET	675.000	226.000	203.000

Annex 2. Table 2. Retail price for 5-LH trucks with a daily driving range of 800 km based on its technology for years 2023, 2030 and 2040 in €. [4]

5-LH (1000 km) truck's retail price (€)			
	2023	2030	2040
Diesel	176.000	192.000	192.000
HVO	176.000	192.000	192.000
BET	457.000	239.000	218.000
Bio-CNG	188.000	200.000	198.000
e-Diesel	176.000	192.000	192.000
FCET	688.000	236.000	211.000

Annex 2. Table 3. Retail price for 5-LH trucks with a daily driving range of 1000 km based on its technology for years 2023, 2030 and 2040 in €. [4]

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