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Master thesis

Total Cost of Ownership (TCO):

a new model to estimate the cost of trucks

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Abstract

The transport sector is one of the major contributors to CO_2 and greenhouse gases (GHG) emissions, significantly contributing to climate change. Nowadays, the vehicles used in this sector – and in particular in the heavy-duty transport sector, which is the focus of this report – are mainly internal combustion engine (ICE) Diesel trucks.

The goal is to progressively replace these vehicles with trucks powered by zero-impact sources on the environment, such as hydrogen and electricity that can be produced through renewable energy sources and therefore without (or with low) CO_2 emissions.

In order to study the feasibility of this operation and to better understand when this transition from conventional trucks to alternative ones would be feasible, the aim of this work is to develop a new model for the estimation of the Total Cost of Ownership (TCO), improving with new data existing models in the literature. Many parameters are considered in order to build this model, such as the country in which the truck is registered, that influences the taxation applied to the vehicle, the number of working days during a year, the cost of all the components (chassis, battery, powertrains, hydrogen tank, fuel cell module, etc.), the infrastructure cost, the energy/fuel cost, and the truck consumption.

The alternative powertrains analysed are two: Fuel Cell Electric Trucks (FCET) and Battery Electric Trucks (BET). In turn, the first could be further divided into three different groups according to the conditions in which the hydrogen is stored on board: FCET with gaseous hydrogen at 350 bar, FCET with gaseous hydrogen at 700 bar, and FCET with liquid hydrogen at -253°C.

Furthermore, three different truck typologies are considered as a reference for this model: tractor 4x2 (with a power of 330 kW and a total gross weight of 40 t), rigid 6x2 (with a power of 270 kW and a total gross weight of 27 t), and rigid 4x2 (with a power of 220 kW and a total gross weight of 18 t).

The result obtained from the model is that alternative powertrains are expected to be economically competitive in the short to medium period according to their application and that FCET are more competitive than BET for long-haul segment, whereas electric trucks are the best solution for short and medium routes.

Therefore, the objective of this model is to identify the parameters that have a greater impact on the TCO of the vehicle in order to understand in which direction Governments must go to

reach the decarbonization goals as soon as possible, and the result is that the parameters that most affect the TCO are the road toll, the energy/fuel cost, the annual mileage, the driving profile, and the market maturity.

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1. Introduction

As CO_2 and Greenhouse Gases (GHGs) emissions related to human activities are continuously increasing, with significant impacts on the environment and the planet's climate, the European Union (EU) has established a series of increasingly stringent limits for the emissions of these gases: all these policy initiatives are called European Green Deal and its aim is to achieve climate neutrality for Europe in 2050. The ambitions of the Green Deal are converted into laws thanks to the "Fit for 55" package that consists of recommendations to update climate, energy, and transportation legislation as well as to implement new legislative efforts to align EU laws with the EU's climate goals. By applying these climate laws, the European States want to cut net GHG emissions by at least 55% by 2030 with respect to 1990 levels [1].

Transport sector is responsible for almost 25% of GHG emissions in the EU and around 71% of them are due to road transport (Figure 1.1):

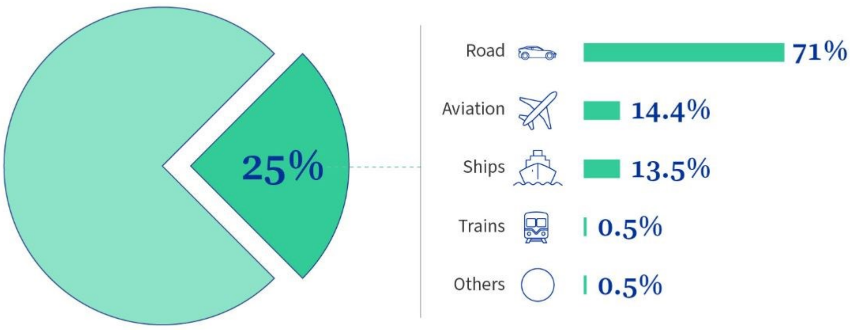

Figure 1.1 GHG emissions by transport sector [2]

Trucks and buses account for around 25% of CO_2 emissions from road transport in European Union and for around 5% of overall EU GHG emissions [3]. Despite recent gains in fuel consumption efficiency, these emissions continue to rise, owing primarily to an increases in road freight traffic.

To reverse this trend and reduce CO_2 emissions, in 2023 new stricter targets have been proposed by European Commission [3][4]:

- -15% of GHG emissions compared to 2019 levels within 2025;
- -45% of GHG emissions compared to 2019 levels within 2030;
- -60% of GHG emissions compared to 2019 levels within 2035;
- -90% of GHG emissions compared to 2019 levels within 2040.

To achieve these targets, conventional truck fleets must be entirely or partially substitute by alternative powertrain trucks that are zero-emission vehicles.

This work divides trucks into three different categories and for each of them different alternative powertrains are considered.

1.1 Alternative powertrains

Alternative powertrains can be classified into two main groups: Fuel Cell Electric Trucks (FCET) and Battery Electric Trucks (BET).

In the first technology, the fuel is hydrogen and it can be classified with different "colours" depending on its source:

- *green* hydrogen if it is produced by biomass, biogas, or 100% renewable energy;
- *pink* hydrogen if it is produced by nuclear energy;
- *grey* hydrogen if it is produced by natural gas with steam methane reforming without carbon capture;
- *brown* hydrogen if it is produced by coal gasification without carbon capture;
- *blue* hydrogen if it is produced by natural gas with steam reforming and carbon capture or by coal gasification and carbon capture.

In order to be considered zero-emissions trucks, FCETs need to be powered by green hydrogen.

One of the main components of FCET is the fuel cell module (FC) that is a series of electrochemical cells that allow the production of electrical energy through the chemical reaction between hydrogen (the fuel) and oxygen provided by the external air taken from the environment. A scheme of a fuel cell is reported in Figure 1.2:

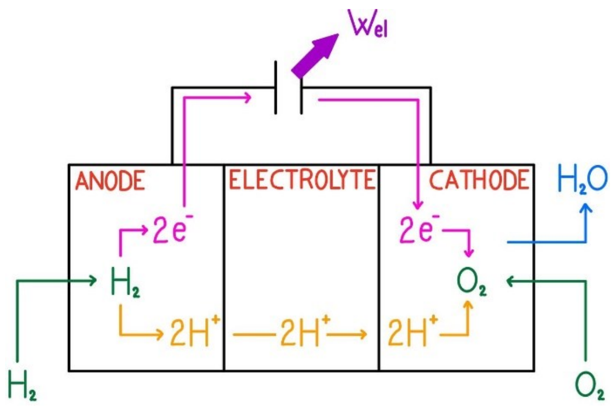

Figure 1.2 Fuel Cell scheme

The electrolyte is a material containing ions with good mobility that allows the H^+ transfer from the anode to the cathode. In the anode and cathode take place the two half reactions of oxidation and reduction, respectively:

Half reaction of oxidation: $$H_2 \rightarrow 2H^+ + 2e^- \tag{1.1}$$

Half reaction of reduction: $$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \tag{1.2}$$

Complete redox reaction: $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1.3}$$

The charge separation determines a voltage gradient at both anode and cathode and the difference between these two voltage gradients generates a voltage gradient at the cell level that, with the current due to the passage of the electron from the anode to the cathode, generates electrical power. There are other two products in this process: water in form of vapour and heat that is dissipated into the environment.

The second main component is the hydrogen tank which determines the different types of FC vehicle that can be categorised into three types: FCET with gaseous hydrogen at 350 bar, FCET with gaseous hydrogen at 700 bar, and FCET with liquid hydrogen at -253°C. The storage of hydrogen as a gas at high pressure allows to reduce the dimension of the tank thanks to the reduced density of hydrogen at high pressure (at 700 bar the hydrogen density is around 42 kg/m^3) or to store more mass in the same volume. Thus, the tank for storing hydrogen at 350 bar is larger than the one for hydrogen at 700 bar, and in fact the storage tank at 700 bar is mainly used for light-duty vehicles (in which the space is reduced), whereas the storage at 350 bar is mainly used for heavy-duty vehicles. Finally, storage of liquid hydrogen requires maintaining a very low temperature, so insulation and refrigeration are very important. One of the flaw of liquid hydrogen is its low energy density compared to other conventional fuels.

The second alternative powertrains considered in the model is the electric one. The electric motor of BET converts the electrical energy stored in the battery into the mechanical energy needed to move the truck. The electrical energy stored in the battery is transmitted to the electric motor by an inverter, a device that converts the direct current from the battery to alternating current and sends it to the motor. The main problem with this technology today is the battery and its autonomy, which cannot be compared with the autonomy of Diesel trucks. By comparing different electric trucks (Scania and Volvo models) with conventional trucks (Iveco model), the results is that today the autonomy for electric trucks is around 300-350 km [5][6], whereas for Diesel trucks is over 900 km [7].

1.2 Trucks classification

Trucks are usually classified with respect to some common parameters, mainly their gross vehicle weight ("is total of the weight of the vehicle (or combination of vehicles) including its load when stationary and ready for the road declared permissible by the competent authority of the country of registration. This includes the weight of the driver and the maximum number of persons permitted to be carried." [8]), their axle configuration and their chassis configuration.

They are classified as rigid trucks or road tractors based on their chassis: in a rigid truck, the cargo, the power unit, and the cab are on the same chassis, while a tractor is used to tow a semi-trailer which is used to transport a load. Without a semi-trailer, a tractor can not transport any load.

The trucks considered in this work are the heavy-duty trucks that are the vehicles that mainly contribute to the CO_2 emissions: without any action, the emissions increase from 6% to 9% within 2030. Thus, these types of trucks are the first categories that must be substitute in order to reduce the CO_2 emissions. In particular, the trucks mentioned by the European legislation [9] are the tractor 4x2, which means that it has 4 wheels (2 axes) of which 2 are drive wheels, the rigid 6x2, which means that it has 6 wheels (3 axes) of which 2 are drive wheels, and rigid 4x2, which means that it has 4 wheels (2 axes) of which 2 are drive wheels. For this reason, this work is focused on these typologies of trucks.

Each type of truck is assumed to be used for a different purpose for the analysis in the next sections:

- Tractor 4x2 (with a gross weight of 40 tonnes), used for long distances, national or international logistics, and their annual mileage is around 140.000 km/year;
- Rigid 6x2 (with a gross weight of 27 tonnes), used for medium distances, national or regional logistics, and their annual mileage is around 95.000 km/year;
- Rigid 4x2 (with a gross weight of 8 tonnes), used for short distances, regional logistics, and their annual mileage is around 60.000 km/year.

The share of these trucks in the market (in 2022) is reported in Table 1.1 [10]:

Table 1.1 Share of trucks by typology in Europe (2022)

Share of trucks by typology in Europe (2022)		
	Number of trucks	**Percentage of trucks**
Total trucks sale	~310.000	100 %
Tractor trucks 4x2	~100.000	32 %
Rigid trucks 6x2	~20.000	6 %
Rigid trucks 4x2	~70.000	23 %

As said before, to achieve these targets, conventional truck fleets must be entirely or partially substitute by alternative powertrain trucks that are zero-emission vehicles, but this is not possible with the current market maturity of these alternative trucks. Then, it is important to study and analyse the competitiveness of these trucks compared to Diesel trucks over years, in order to understand when the transition can be possible with the current situation in terms of market maturity, cost of components, and taxations, and to understand which parameters must be adjusted to accelerate the transition. To do this, a Total Cost of Ownership (TCO) model can be used, where the TCO is an estimate of all the direct and indirect costs involved in acquiring and operating a truck.

2. Model

The TCO model aims to study the feasibility to produce trucks powered by innovative powertrains and fuels, such as FCET and BET, that can be considered as zero-emission powertrains. The truck typologies used as a reference in this model, as already done in the model proposed by Roland Berger [11], are three:

- Tractor 4x2 (330 kW)
- Rigid 6x2 (270 kW)
- Rigid 4x2 (220 kW)

Each typology is assumed to be used for different mileage: tractor 4x2 is used for long-haul segment (110.000-200.000 km/year), rigid 6x2 for mid-haul segment (70.000-110.000 km/year), and rigid 4x2 for short-haul segment (10.000-70.000 km/year).

The model is composed by two main sections: input parameters and results. In turn, the input parameters section is divided into 4 different subsections (Table 2.1):

Table 2.1 Classification of input parameters

Input parameters			
General parameters	**Energy and fuel parameters**	**Correction factors**	**Specific parameters**
- Country	- Cost without taxation	- Annual mileage	- Truck power
- Working days	- Taxation	- Driving profile	- Chassis cost
- Life	- Infrastructure surcharges	- Type of refuelling	- Powertrain cost
- Large battery	- Ad-Blue cost	- Taxation and surcharges	- FC module cost
- Small battery	- CO_2 emissions	- Motor vehicle tax	- H_2 tank cost
- Maintenance cost	- Infrastructure cost	- Road toll	- Battery capacity
- Motor vehicle tax		- Maturity of technology	- Lifetime
- Insurance cost			- Consumptions
- Registration fee			- Payload
- Road toll			

2.1 Input parameters

These sections include all those values useful to define general and specific parameters related to the truck life, such as cost and size of components, cost related to maintenance and taxation, cost related to energy and fuel, information about working conditions of the truck, CO_2 emissions, payload, and other parameters.

The model suggests the input parameters according to several studies and to the literature, but every parameter can be modified with a different value with respect to the suggested one in order to customise the analysis and to adapt it to a specific case study. The values suggested by the model are reported in the following tables in order to give an idea of the parameters used here. So, all the results obtained and commented in the following chapters are referred to these values.

2.1.1 General parameters

These parameters allow to describe the main settings that do not depend on the truck type.

- **Country**

Some parameters are specific for each country, so the choice of the country is important to have a better estimation of the TCO. The parameters related to the country are motor vehicle tax, registration fee, road toll, Diesel price, and share of empty runs, i.e., the percentage of runs with zero payload.

The countries from which it is possible to choose among are Albania, Croatia, Czechia, France, Germany, Greece, Hungary, Ireland, Italy, Norway, Poland, Portugal, Slovakia, Spain, and United Kingdom. There is another option called "Other", thanks to which all the parameters mentioned above are set to zero. In this case the user must enter the values manually.

- **Working days**

It represents the number of days in a year when the truck is expected to work. To get this number, it is necessary to consider that, on average, in a year there are 52 Saturdays and Sundays plus all holidays.

The suggested value from the model is 250 days/year.

- **Life of the truck**

It represents the number of years in which is expected that the truck works and it is divided into first life and second life. The first life of trucks is linked to their initial use as a new vehicles (about 5 years), while the second life refers to their use in a market for used trucks (additional about 5 years).

- **Large battery**

The large battery is the main powertrain of BET, so it is important to define three parameters:

- *Specific cost*, in €/kWh, in order to evaluate the total cost of the component (Table 2.2);

- *Energy density*, in kWh/kg, to evaluate the payload reduction with respect Diesel trucks (Table 2.3);
- *Battery buffer*, a percentage of the battery capacity in order to assure reach and to preserve the integrity of the battery. It is evaluated according to the additional reach necessary and the percentage of utilisation that assures the integrity of the battery:

$$buffer = \frac{additional\ reach \cdot (1 - utilisation)}{utilisation} \quad (2.1)$$

The suggested values of specific costs and energy densities are summarised in the following tables [11]:

Table 2.2 Large battery specific cost

Specific cost [€/kWh]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	280	278	276	275	273	271	269	267
Rather niche	208	207	205	203	202	200	199	197
Rather mass	167	165	164	162	161	160	158	157
Mass	142	141	140	139	137	136	135	133

Table 2.3 Large battery energy density

Energy density [kWh/kg]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
All markets	0,176	0,176	0,176	0,187	0,199	0,210	0,222	0,233

- **Small battery**

The small batter is used in FCET in order to avoid that the mileage covered by the fuel is not enough, so it is used as range extender. Even in this case, it is necessary to define some parameters:

- *Specific cost*, in €/kWh, in order to evaluate the total cost of the component (Table 2.4);
- *Energy density*, in kWh/kg, to evaluate the payload reduction with respect to Diesel trucks (Table 2.5).

The suggested values of the specific costs and of the energy density are summarised in the following tables [11]:

Table 2.4 Small battery specific cost

Specific cost [€/kWh]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	364	362	359	357	355	352	350	348
Rather niche	271	269	267	264	262	260	258	256
Rather mass	216	215	213	211	209	208	206	204
Mass	185	184	182	180	178	177	175	173

Table 2.5 Small battery energy density

Energy density [kWh/kg]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
All markets	0,141	0,141	0,141	0,150	0,159	0,168	0,177	0,186

- **Maintenance cost**

It is a value that represents how many €/km are needed for the maintenance of the truck, only including ordinary maintenance, like revision and tires change. This cost is different according to the typology of truck (Table 2.6) [12]:

Table 2.6 Maintenance cost

Maintenance cost [€/km]	
Diesel	0,12
FCET	0,11
BET	0,11

- **Motor vehicle tax**

This parameter refers to vehicle taxation, mandatory to move in most European countries. In some cases, it may not be considered whether the country applies incentives on a particular technology, for example to promote sustainable transport with low-carbon emissions.

It can be evaluated in two different ways:

- like an average percentage value of the total cost of the vehicle, in order to take into consideration a single value for all countries;
- according to the different country taxation.

The first method is easier, but less precise, so this model considers a different value, equal for each technology and constant over years, according to the country (Table 2.7) [13][14][15][16][17][18]:

Table 2.7 Motor vehicle tax

Motor vehicle tax [€]	
Albania	171,00
Croatia	156,08
Czechia	113,58
France	516,00
Germany	373,24
Greece	381,51
Hungary	913,90
Ireland	900,00
Italy	654,99
Norway	203,68
Poland	400,00
Portugal	389,00
Slovakia	1817,00
Spain	587,30
United Kingdom	541,23

- **Insurance cost**

The cost of insurance represents a mandatory cost that the owner of a vehicle must pay to drive on the road. It covers the driver from the possibility of an accident and it is evaluated as a percentage of the total vehicle cost, particularly the assumed value is 1,50% of the total purchase cost [19].

- **Registration fee**

It is a tax that the owner of a vehicle must pay when the vehicle is purchased or when it is resold. It depends on the country in which the vehicle is bought and registered. The values are reported in Table 2.8 [13][14][15][16][17][18]:

Table 2.8 Registration fee

Registration fee [€]	
Albania	36,66
Croatia	66,14
Czechia	33,64
France	154,00
Germany	42,15
Greece	75,00
Hungary	40,31
Ireland	200,00
Italy	101,20
Norway	240,60
Poland	150,00
Portugal	45,00
Slovakia	66,00
Spain	54,60
United Kingdom	64,36

- **Road toll**

The road toll is a tax that is paid when a vehicle uses a portion of motorway. Each country can have or not this road toll according to the policy of the specific country: if a country has this tax, usually it is not fixed but depends on the portion of motorway interested in the route of the vehicle.

A representative mean value for the road toll for each country is summarised in Table 2.9 [20][21][22][23][24][25]:

Table 2.9 Road toll

Road toll [€/km]	
Albania	0,04
Croatia	0,06
Czechia	0,19
France	0,08
Germany	0,17
Greece	0,07
Hungary	0,15
Ireland	0,16
Italy	0,08
Norway	0,12
Poland	0,13
Portugal	0,07
Slovakia	0,19
Spain	0,10
United Kingdom	0,23

2.1.2 Energy and fuel parameters

The cost of fuel/energy is divided in three parts:

- *Cost without taxation and surcharges*, the cost of the raw material (Table 2.10);
- *Cost of taxation*, it depends on fuel type (Diesel, H_2, or electricity) and on government policy (Table 2.11);
- *Cost of infrastructure surcharges*, it depends on the infrastructure type, whether it is private or public and on its maintenance. Regarding the FCET, this component is different from the different typology (350 bar, 700 bar, and LH_2) (Table 2.12).

These cost components are reported in the following tables for FCET and BET [11]:

Table 2.10 Energy/Fuel cost without taxation and surcharges

Energy/Fuel cost without taxation and surcharges									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
FCET	€/kg	3,15	3,00	2,86	2,73	2,60	2,48	2,36	2,25
BET	€/kWh	0,05	0,05	0,05	0,05	0,04	0,04	0,04	0,04

Table 2.11 Energy/Fuel taxation cost

Energy/Fuel taxation cost									
		2023	2024	2025	2026	2027	2028	2029	2030
FCET	€/kg	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
BET	€/kWh	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10

Table 2.12 Energy/Fuel infrastructure surcharges cost

Energy/Fuel infrastructure surcharges cost									
		2023	2024	2025	2026	2027	2028	2029	2030
FCET 350 bar	€/kg	3,75	3,49	3,25	3,02	2,81	2,61	2,42	2,25
FCET 700 bar	€/kg	4,15	3,87	3,61	3,37	3,15	2,93	2,74	2,55
FCET LH_2	€/kg	4,55	4,20	3,87	3,56	3,28	3,02	2,77	2,55
BET	€/kWh	0,15	0,14	0,12	0,11	0,10	0,09	0,07	0,06

For Diesel the cost depends on the country, so the values are reported in Table 2.13 [26][27]:

Table 2.13 Diesel cost for each country

Diesel cost [€/l]			
	Without taxation and surcharges	Taxation	Surcharges
Albania	0,92	0,44	0,29
Croatia	0,92	0,41	0,29
Czechia	0,89	0,39	0,23
France	0,93	0,59	0,35
Germany	0,91	0,49	0,34
Greece	0,96	0,41	0,36
Hungary	0,95	0,31	0,32
Ireland	0,91	0,54	0,23
Italy	0,88	0,62	0,34
Norway	0,92	0,44	0,29
Poland	0,89	0,33	0,29
Portugal	0,88	0,51	0,16
Slovakia	0,90	0,37	0,30
Spain	0,94	0,38	0,29
United Kingdom	1,00	0,67	0,27

The cost of Diesel without taxation and surcharges is assumed constant over the years, while taxation and surcharges are considered as variable over the years. Particularly, for both are assumed to increase by one cent per year until 2030.

If the fuel is Diesel, it is necessary to take into account also the Ad-Blue fuel, a fluid used to reduce the NO_x emissions (Table 2.14) [28].

Table 2.14 Ad-Blue cost

Ad-Blue cost [€/l]								
	2023	2024	2025	2026	2027	2028	2029	2030
Ad-Blue	0,70	0,70	0,70	0,70	0,70	0,70	0,70	0,70

- **CO_2 emissions**

Linked to Diesel fuel, there are CO_2 emissions. This value is used to evaluate how many gCO_2 are emitted for each tonne-kilometre (tonne-kilometre is a unit of measure of freight transport which represents the possible transport of tonne of goods by a given transport mode over a distance of one kilometre). The emissions are divided into two components: "well to tank" and "tank to wheel". Then, they are summed to obtain the total emissions (Table 2.15) [29]:

Table 2.15 CO_2 emissions

CO_2 emission							
		Well to tank	**Tank to wheel**	**Well to wheel**	**Well to tank [%]**	**Tank to wheel [%]**	**Well to wheel [%]**
Diesel	gCO_2/l	568,425	2.718,105	3.286,530	17,30 %	82,70 %	100 %
FCET	gCO_2/kg	0,00	0,00	0,00	0,00 %	0,00 %	0 %
BET	gCO_2/kWh	0,00	0,00	0,00	0,00 %	0,00 %	0 %

As it is possible to see from the table above, the majority of the CO_2 emissions (around 80%) are due to the "tank to wheel" contribution, which is the part of the process in which the fuel is converted into the truck engine from Diesel to energy at wheel necessary to move the truck. The remaining part, around 20%, is CO_2 emitted in the preparation of the fuel in factories and so it is not strictly related to the transportation of goods by the truck.

- **Infrastructure cost**

The last parameter related to the energy and fuel is the infrastructure cost: it mainly depends on the type of fuel. In addition to the cost of installation, there is the maintenance cost, evaluated as percentage of the total investment cost. Then, the total infrastructure cost is given by (2.2):

$$total\ infrastruct.cost = infrastruct.cost \cdot (1 + maintenance\ cost) \tag{2.2}$$

For Diesel trucks, the infrastructure cost is assumed null, since it already exists and it is quite widespread, whereas for the other trucks the values are reported in Table 2.16 [11][30]:

Table 2.16 Infrastructure cost

Infrastructure cost [€/vehicle]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0	0	0	0	0	0	0	0
FCET 350 bar	89.417	87.805	86.229	84.688	79.413	77.474	75.594	74.278
FCET 700 bar	125.183	122.927	120.721	118.563	111.178	108.463	105.832	103.989
FCET LH_2	98.358	96.595	94.852	93.157	87.354	85.221	83.154	81.705
BET	77.250	75.821	74.393	72.964	68.821	67.464	66.107	62.250

The infrastructure maintenance cost is assumed as a percentage of the total infrastructure cost (Table 2.17) [31][32]:

Table 2.17 Infrastructure maintenance cost

Infrastructure maintenance cost	
Diesel	0,00 %
FCET	4,00 %
BET	5,00 %

2.1.3 Customizable input parameters

It is then possible to adjust all the previously described parameters according to the different scenarios, modifying the annual mileage, the typology of infrastructure, the fuel taxation, and the maturity of technology according to some correction factors.

- **Annual mileage**

Each truck typology has its annual mileage that can be set from a dedicated input menu. The model gives the possibility to set the annual mileage starting from 10.000 km/year to 200.000 km/year.

According to the previous definition of truck typologies, the model suggests some values for each truck type (Table 2.18):

Table 2.18 Annual mileage for each truck type

Annual mileage [km/year]		
Tractor 4x2	Long-haul segment	140.000
Rigid 6x2	Mid-haul segment	95.000
Rigid 4x2	Short-haul segment	60.000

- **Homogeneity of driving profile**

This part allows the selection of the driving profile choosing from homogeneous to heterogeneous, taking into account a coefficient that modifies the capacity of the H_2 tank and the battery size. The suggested coefficients are summarised in Table 2.19:

Table 2.19 Driving profile correction factors

Driving profile	Factor
Homogeneous	1,10
Rather homogeneous	1,25
Rather heterogeneous	1,50
Heterogeneous	1,75

This factor is customizable and it can assume any value, but the model suggests using 1,25.

- **Refuelling infrastructure**

The refuelling infrastructure can be private, public or both private and public. According to this selection, the infrastructure cost can be taken into consideration or not. The model gives the chance to select a different percentage for public and private refuelling (e.g., 30% public and 70% private). The suggestion of the model is not to consider this cost.

- **Energy/Fuel taxation and infrastructure surcharges**

As previously mentioned, the cost of energy/fuel is influenced by the taxation and the infrastructure surcharges. In this section it is possible to choose if taxation is totally, partially or not considered. In addition, the selection of public refuelling in the previous menu implies that the cost of infrastructure surcharges is considered proportionally at the percentage of public refuelling.

- **Total energy/fuel cost**

The total energy/fuel cost, whose components has already been set in the previous sections, is adjusted taking into account the refuelling type and the taxation contribution. The final cost is obtained according to (2.3):

$$total\ cost = A + B \cdot d + C \cdot d \cdot f \tag{2.3}$$

where:

- A is the cost of fuel/energy without taxation and infrastructure surcharges;
- B is the cost of fuel/energy taxation;
- C is the cost of infrastructure surcharges;
- d is the percentage of taxation that depends on the legislation;
- f is the percentage of public refuelling selected in the previous section.

- **Motor vehicle tax**

Motor vehicle tax can be considered or not, according to the government policy. In this way it is possible to consider incentives for innovative technologies or to increase the taxation for Diesel trucks in order to go towards carbon neutrality. The model gives the possibility to split the time period in two parts: from 2023 to 2030 and from 2031 to 2040. In this way it is possible to follow a transition between high and low taxation. The corrected motor vehicle tax is given by (2.4):

$$corrected\ motor\ vehicle\ tax = motor\ vehicle\ tax \cdot corrected\ factor \tag{2.4}$$

where the corrected factor is a percentage value between 0% and 100%.

- **Road toll**

The road toll is discussed in the same way as motor vehicle tax: it is possible to select the percentage of the base road toll, also different for truck types, according to the government policy, favouring low-emission engines over Diesel powertrains. The corrected road toll is given by (2.5):

$$corrected\ road\ toll = road\ toll \cdot corrected\ factor \tag{2.5}$$

- **Technology maturity**

This is one of the most important parameters for the evaluation of the TCO. Each component has different market and technology maturity, so its cost is different according to its maturity. In this model four different scenarios are considered:

- *Niche market*, production lower than 5.000 unit/year;
- *Rather niche market*, production higher than 5.000 unit/year, but lower than 10.000 unit/year;
- *Rather mass market*, production higher than 10.000 unit/year, but lower than 150.000 unit/year;
- *Mass market*, production higher than 150.000 unit/year.

The model gives the possibility to change the market maturity every 4 years (2023-2026, 2027-2030, 2031-2034, 2035-2038, 2039-2040), but it is assumed that the market maturity of Diesel trucks has already reached the mass market level in 2023.

The model sets the market maturity in the following way:

Table 2.20 Market maturity

Market maturity				
	2023-2026	**2027-2030**	**2031-2034**	**2035-2040**
Diesel	Mass	Mass	Mass	Mass
FCET 350 bar	Niche	Rather niche	Rather mass	Mass
FCET 700 bar	Niche	Rather niche	Rather mass	Mass
FCET LH_2	Niche	Rather niche	Rather mass	Mass
BET	Niche	Rather niche	Rather mass	Mass

2.1.4 Specific parameters

In this section of the model all the values related to the specific truck type are set, such as chassis cost, powertrain cost, H_2 tank cost, fuel/energy consumption, and truck weight.

- **Truck power**

The truck engine power is chosen according to the truck type and on its different application (Table 2.21):

Table 2.21 Truck power

Truck power [kW]	
Tractor 4x2	330
Rigid 6x2	270
Rigid 4x2	220

- **Truck chassis cost (without powertrain)**

This cost is considered the same for all the technologies and for all years and it is obtained through a market analysis in order to obtain an average value to simplify the model (Table 2.22) [11]:

Table 2.22 Truck chassis cost

Truck chassis cost [€]	
Tractor 4x2	63.000
Rigid 6x2	58.100
Rigid 4x2	54.600

- **Powertrain cost**

The main powertrains involved in this model are two: Diesel powertrain and E-Drive powertrain. The first one is the powertrain of Diesel trucks, whereas the second is the powertrain for FCET. Concerning Diesel powertrain, the market maturity is considered as mass market starting from 2023 because the technology has been already tested and it is commercialised for many years, whereas the FCET powertrain can be considered at different market levels in order to have a more complete model. The suggested values, taking from literature [11], are reported in Table 2.23, Table 2.24, Table 2.25, and Table 2.26:

Table 2.23 Diesel powertrain cost

Diesel powertrain [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Tractor 4x2	24.000	24.000	26.500	26.500	26.500	26.500	26.500	26.500
Rigid 6x2	19.500	19.500	21.550	21.550	21.550	21.550	21.550	21.550
Rigid 4x2	17.500	17.500	19.325	19.325	19.325	19.325	19.325	19.325

Table 2.24 E-Drive powertrain cost (tractor 4x2)

Tractor 4x2 - E-Drive powertrain [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	37.401	37.041	36.680	36.320	35.959	35.598	35.238	34.877
Rather niche	20.689	20.429	20.170	19.910	19.650	19.391	19.131	18.871
Rather mass	13.539	13.337	13.135	12.933	12.731	12.529	12.327	12.125
Mass	10.466	10.278	10.091	9.903	9.716	9.528	9.341	9.153

Table 2.25 E-Drive powertrain cost (rigid 6x2)

Rigid 6x2 - E-Drive powertrain [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	34.341	34.046	33.751	33.456	33.161	32.866	32.571	32.276
Rather niche	18.486	18.273	18.061	17.848	17.636	17.424	17.211	16.999
Rather mass	11.825	11.660	11.495	11.330	11.165	10.999	10.834	10.669
Mass	8.875	8.721	8.568	8.414	8.261	8.108	7.954	7.801

Table 2.26 E-Drive powertrain cost (rigid 4x2)

Rigid 4x2 - E-Drive powertrain [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	31.791	31.551	31.311	31.070	30.830	30.589	30.349	30.108
Rather niche	16.650	16.477	16.304	16.131	15.957	15.784	15.611	15.438
Rather mass	10.397	10.263	10.128	9.994	9.859	9.724	9.590	9.455
Mass	7.549	7.424	7.299	7.174	7.049	6.924	6.799	6.674

- **Fuel Cell module cost**

The FC module has a net power lower than the truck power according to the typical fuel cell size (Table 2.27):

Table 2.27 Fuel Cell module power

FC module power		
Tractor 4x2	72,7 %	240 kW
Rigid 6x2	66,7 %	180 kW
Rigid 4x2	54,5 %	120 kW

By multiplying the net FC power by the cost per kW of the FC, the cost of the single FC module is obtained for each truck type and market maturity (Table 2.28 - Table 2.30):

Table 2.28 FC module cost (tractor 4x2)

Tractor 4x2 - FC module cost [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	103.200	96.960	91.200	85.920	80.880	76.080	71.520	67.200
Rather niche	57.600	54.000	50.880	47.760	44.880	42.240	39.600	37.200
Rather mass	38.400	36.00	33.600	31.440	29.280	27.360	25.680	24.000
Mass	19.200	18.240	17.280	16.320	15.600	14.640	13.920	13.200

Table 2.29 FC module cost (rigid 6x2)

Rigid 6x2 - FC module cost [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	77.400	72.720	68.400	64.440	60.660	57.060	53.640	50.400
Rather niche	43.200	40.500	38.160	35.820	33.660	31.680	29.700	27.900
Rather mass	28.000	27.000	25.200	23.580	21.960	20.520	19.260	18.000
Mass	14.400	13.680	12.960	12.240	11.700	10.980	10.440	9.900

Table 2.30 FC module cost (rigid 4x2)

Rigid 4x2 - FC module cost [€/unit]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	51.600	48.480	45.600	42.960	40.440	38.040	35.760	33.600
Rather niche	28.800	27.000	25.440	23.880	22.440	21.120	19.800	18.600
Rather mass	19.200	18.000	16.800	15.720	14.640	13.680	12.840	12.000
Mass	9.600	9.120	8.640	8.160	7.800	7.320	6.960	6.660

These values are editable by assuming other values for the cost per kW of the FC module. The values reported in the previous tables are not fixed but only suggested from the model according to the literature [11].

- **H_2 tank cost**

The tank cost evaluation depends on several factors. Basically, the unit cost is given by the product of the cost per kilogram and the H_2 tank capacity (in kg), but in turn, the tank capacity depends on daily mileage, driving profile, buffer, and fuel consumption (analysed in the following steps).

First, it has to be calculated the correct daily mileage as the product of daily mileage and factor of driving profile homogeneity (2.6):

$$correct\ daily\ mileage = \frac{annual\ mileage}{working\ days} \cdot driving\ profile\ factor \tag{2.6}$$

Consequently, the necessary reach is obtained by adding a buffer to the correct daily mileage in order to extend the range and to avoid not having enough fuel to reach the final destination (2.7):

$$necessary\ reach = correct\ daily\ mileage \cdot (1 + buffer) \tag{2.7}$$

Eventually, the H_2 tank capacity is calculated by equation (2.8):

$$H_2\ tank\ capacity = necessary\ reach \cdot consumptions \tag{2.8}$$

From Table 2.31 to Table 2.35 are reported the values for the necessary reach after corrections, for H_2 tank capacity, and for the H_2 tank cost considering the values suggested from the model according to the literature [11]:

Table 2.31 Necessary reach (FCET)

Necessary reach [km]			
	Tractor 4x2	**Rigid 6x2**	**Rigid 4x2**
Daily mileage	560	380	240
Correct daily mileage	700	475	300
Buffer	33,0 %	33,0 %	33,0 %
Necessary reach	931	632	399

Table 2.32 H_2 tank capacity

H_2 tank capacity [kg]								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Tractor 4x2	78	78	77	76	76	75	75	74
Rigid 6x2	47	47	47	46	46	45	45	45
Rigid 4x2	26	26	26	26	26	25	25	25

Table 2.33 H_2 tank cost (tractor 4x2)

Tractor 4x2 - H_2 tank cost [€/unit]								
FCET 350 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	55.046	52.685	50.266	48.114	45.913	43.964	42.036	40.335
Rather niche	42.319	40.580	38.660	37.040	35.324	33.818	32.329	31.033
Rather mass	32.559	31.192	29.745	28.487	27.155	26.002	24.863	23.889
Mass	22.799	21.803	20.829	19.933	18.986	18.187	17.397	16.744
FCET 700 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	59.575	57.107	54.570	52.314	49.998	47.872	45.918	44.131
Rather niche	44.271	42.675	40.966	39.484	37.895	36.524	35.167	33.935
Rather mass	35.604	34.140	32.512	31.160	29.726	28.407	27.178	26.121
Mass	24.907	23.898	22.750	21.766	20.801	19.915	19.039	18.307
FCET LH_2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	28.733	26.924	25.210	23.599	22.087	20.667	19.413	18.233
Rather niche	19.129	17.924	16.755	15.733	14.750	13.828	12.917	12.205
Rather mass	12.805	11.949	11.221	10.463	9.833	9.168	8.661	8.112
Mass	8.901	8.380	7.840	7.332	6.883	6.463	6.048	5.656

Table 2.34 H_2 tank cost (rigid 6x2)

Rigid 6x2 - H_2 tank cost [€/unit]								
FCET 350 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	33.329	31.877	30.489	29.060	27.800	26.600	25.507	24.467
Rather niche	25.623	24.553	23.449	22.371	21.388	20.462	19.617	18.824
Rather mass	19.714	18.873	18.042	17.205	16.442	15.733	15.087	14.490
Mass	13.805	13.192	12.634	12.039	11.495	11.004	10.556	10.157
FCET 700 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	36.071	34.553	33.100	31.597	30.273	28.964	27.863	26.769
Rather niche	26.805	25.821	24.848	23.847	22.945	22.098	21.339	20.585
Rather mass	21.558	20.657	19.720	18.820	17.999	17.188	16.491	15.845
Mass	15.081	14.460	13.799	13.146	12.595	12.050	11.553	11.105
FCET LH_2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	17.397	16.291	15.291	14.253	13.373	12.504	11.780	11.060
Rather niche	11.583	10.845	10.163	9.502	8.931	8.366	7.838	7.403
Rather mass	7.753	7.230	6.806	6.319	5.954	5.547	5.255	4.920
Mass	5.389	5.070	4.755	4.428	4.168	3.910	3.670	3.431

Table 2.35 H_2 tank cost (rigid 4x2)

Rigid 4x2 - H_2 tank cost [€/unit]								
FCET 350 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	19.620	18.757	17.932	17.144	16.394	15.679	15.032	14.416
Rather niche	15.084	14.447	13.792	13.198	12.613	12.061	11.561	11.091
Rather mass	11.605	11.105	10.611	10.151	9.696	9.274	8.891	8.538
Mass	8.126	7.762	7.430	7.103	6.779	6.486	6.221	5.984
FCET 700 bar								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	21.234	20.331	19.467	18.641	17.852	17.073	16.420	15.772
Rather niche	15.779	15.193	14.614	14.069	13.531	13.026	12.576	12.128
Rather mass	12.690	12.155	11.598	11.103	10.614	10.131	9.719	9.336
Mass	8.878	8.508	8.116	7.756	7.427	7.103	6.808	6.543
FCET LH_2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Niche	10.241	9.586	8.993	8.409	7.886	7.371	6.942	6.516
Rather niche	6.818	6.381	5.977	5.606	5.267	4.932	4.619	4.362
Rather mass	4.564	4.254	4.003	3.728	3.511	3.270	3.097	2.899
Mass	3.173	2.983	2.797	2.612	2.458	2.305	2.163	2.021

- **Battery capacity**

As seen in paragraph 2.1.1, the batteries mentioned in the model are two: a large battery as a main powertrain for BET and a small battery as a range extender for FCET. Each of them has own specific cost (Table 2.2 and Table 2.4) and own energy density (Table 2.3 and Table 2.5). The first parameter is used to define the total cost of a single battery by multiplying its value with the battery capacity, whereas the energy density is used to evaluate the weight of the battery and then the cost per tonnes.

The large battery capacity is evaluated according to the necessary reach (2.7) and the energy consumption, like the H_2 tank capacity. Results are summarised in the following tables:

Table 2.36 Necessary reach (BET)

Necessary reach [km]			
	Tractor 4x2	Rigid 6x2	Rigid 4x2
Daily mileage	560	380	240
Correct daily mileage	700	475	300
Buffer	33,3 %	33,3 %	33,3 %
Necessary reach	933	633	400

Table 2.37 Large battery capacity

Large battery capacity [kWh]								
	2023	2024	2025	2026	2027	2028	2029	2030
Tractor 4x2	1.432	1.424	1.416	1.408	1.400	1.392	1.383	1.375
Rigid 6x2	789	784	778	773	767	762	756	751
Rigid 4x2	465	461	458	454	451	447	444	441

Regarding the small battery capacity, it is evaluated assuming an average consumption across all years (Table 2.38) [11]:

Table 2.38 Average small battery consumption

Average consumption [kWh/km]	
Tractor 4x2	1,27
Rigid 6x2	1,14
Rigid 4x2	1,06

Then, it is assumed an extended range of 100 km and finally the small battery capacity is obtained (Table 2.39):

Table 2.39 Small battery capacity

Small battery capacity [kWh]	
Tractor 4x2	127
Rigid 6x2	114
Rigid 4x2	106

- **Lifetime and residual value**

Lifetime and scrap value of the main components are assumed based on the Diesel powertrain as incumbent technology (Table 2.40) [11]:

Table 2.40 Lifetime and residual value

	Lifetime [km]	Scrap value [%]
Diesel powertrain	1.400.000	10,0 %
E-Drive powertrain	1.400.000	10,0 %
FC stack	1.400.000	10,0 %
Small battery	1.400.000	10,0 %
H_2 tank 350 bar	1.400.000	0,0 %
H_2 tank 700 bar	1.400.000	0,0 %
H_2 tank LH_2	1.400.000	0,0 %
Large battery	700.000	10,0 %

Large battery has a shorter lifetime than the other components: this limitation is due to the limited number of charging cycle with fast charging.

The scrap value of the tank is null because is difficult to reuse these materials for a second purpose. So, it is assumed that the residual value of the tank is used to cover the waste deposition cost, but the model allows to modify this choice setting a scrap value different than 0,0%.

- **Consumptions**

The energy/fuel consumption is the most important parameter in the TCO evaluation: as it will be demonstrated, the energy/fuel OPEX is the largest component of TCO.

Diesel powertrain consumption is evaluated as a function of the net payload (in tonnes) according to the following relationships obtained through the interpolation of several data [33]. Each truck typology has its relationship:

Tractor 4x2 $$Diesel\ consumption = 1{,}6619 \cdot payload\ [\mathrm{t}] + 2{,}8612 \tag{2.9}$$

Rigid 6x2 $$Diesel\ consumption = 2{,}8415 \cdot payload\ [\mathrm{t}] + 2{,}4309 \tag{2.10}$$

Rigid 4x2 $$Diesel\ consumption = 4{,}1547 \cdot payload\ [\mathrm{t}] + 2{,}6704 \tag{2.11}$$

The ranges of validity of these relationships are the following:

- Tractor 4x2: payload between 17 and 22 tonnes;
- Rigid 6x2: payload between 8 and 11 tonnes;
- Rigid 4x2: payload between 5 and 7 tonnes.

These relationships are useful to obtain the fuel consumption, evaluated in l/100 km, in 2023, whereas for the following years is assumed that there is a constant increase equal to +0,20 l/100 km until 2030, then the values is constant. For the other powertrains the consumption is calculated based on Diesel consumption and energy efficiency (FCET and BET) [11][34].

From Diesel consumption, the energy at wheel is calculated and it is assumed to be the same for all technologies but different for truck type (Table 2.41). To obtain the energy at wheel, the following procedure is applied:

$$energy\ consumption = fuel\ consumption \cdot energy\ content \tag{2.12}$$

$$energy\ at\ wheel = energy\ consumption \cdot efficiency \tag{2.13}$$

Table 2.41 Energy at wheel

Energy at wheel									
Tractor 4x2									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Fuel consumption	l/100 km	35,17	34,97	34,77	34,57	34,37	34,17	33,97	33,77
Energy content	kWh/l	10,335	10,335	10,335	10,335	10,335	10,335	10,335	10,335
Energy consumption	kWh	363,47	361,40	359,33	357,27	355,20	353,13	351,06	349,00
Drivetrain efficiency	%	38 %	38 %	38 %	38 %	38 %	38 %	38 %	38 %
Energy at wheel	kWh	138,12	137,33	136,55	135,76	134,98	134,19	133,40	132,62
Rigid 6x2									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Fuel consumption	l/100 km	28,80	28,60	28,40	28,20	28,00	27,80	27,60	27,40
Energy content	kWh/l	10,335	10,335	10,335	10,335	10,335	10,335	10,335	10,335
Energy consumption	kWh	297,65	295,58	293,51	291,45	289,38	287,31	285,25	283,18
Drivetrain efficiency	%	36 %	36 %	36 %	36 %	36 %	36 %	36 %	36 %
Energy at wheel	kWh	107,15	106,41	105,67	104,92	104,18	103,43	102,69	101,94
Rigid 4x2									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Fuel consumption	l/100 km	27,10	26,90	26,70	26,50	26,30	26,10	25,90	25,70
Energy content	kWh/l	10,335	10,335	10,335	10,335	10,335	10,335	10,335	10,335
Energy consumption	kWh	280,08	278,01	275,94	273,88	271,81	269,74	267,68	265,61
Drivetrain efficiency	%	34 %	34 %	34 %	34 %	34 %	34 %	34 %	34 %
Energy at wheel	kWh	95,23	94,52	93,82	93,12	92,42	91,71	91,01	90,31

Then, the energy/fuel consumption is obtained for FCET and BET for all truck types (Table 2.42):

Table 2.42 Energy/Fuel consumption

Energy/Fuel consumption										
Tractor 4x2										
			2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	Consumption	l/km	0,352	0,350	0,348	0,346	0,344	0,342	0,340	0,338
FCET	Consumption	kg/km	0,092	0,092	0,091	0,091	0,090	0,090	0,089	0,089
BET	Consumption	kWh/km	1,535	1,526	1,517	1,508	1,500	1,491	1,482	1,474
Rigid 6x2										
			2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	Consumption	l/km	0,288	0,286	0,284	0,282	0,280	0,278	0,276	0,274
FCET	Consumption	kg/km	0,075	0,074	0,074	0,073	0,073	0,072	0,072	0,071
BET	Consumption	kWh/km	1,246	1,237	1,229	1,220	1,211	1,203	1,194	1,185
Rigid 4x2										
			2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	Consumption	l/km	0,271	0,269	0,267	0,265	0,263	0,261	0,259	0,257
FCET	Consumption	kg/km	0,070	0,069	0,069	0,068	0,068	0,067	0,067	0,066
BET	Consumption	kWh/km	1,161	1,153	1,144	1,136	1,127	1,118	1,110	1,101

The fuel consumption must be evaluated also for the Ad-Blue fuel used in Diesel powertrains. It is calculated as 5% of the Diesel consumption, so the values obtained are reported in Table 2.43 [35]:

Table 2.43 Ad-Blue consumption

Ad-Blue consumption [l/km]								
Tractor 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Ad-Blue consumption	0,018	0,017	0,017	0,017	0,017	0,017	0,017	0,017
Rigid 6x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Ad-Blue consumption	0,014	0,014	0,014	0,014	0,014	0,014	0,014	0,014
Rigid 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Ad-Blue consumption	0,014	0,013	0,013	0,013	0,013	0,013	0,013	0,013

- **Payload and truck weight adaption**

Each truck typology has its own payload that is reduced or increased according to technology and components. The items making up the payload are:

- Payload gain from reduced weight of new powertrain components (Table 2.44);
- Payload gains due to regulation (Table 2.45);
- Payload loss due to small battery (Table 2.46);
- Payload loss due to large battery (Table 2.47).

The payload gain of alternative powertrains, due to reduced weight of new components, depends on the truck type and on the maturity of the technology and it is assumed that the size, and therefore the weight, of the components will be reduced over the years [11]:

Table 2.44 Payload gain from reduced weight of new powertrain components

Payload gain from reduced weight of new powertrain components [t]								
Tractor 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,90	0,91	0,92	0,93	0,93	0,94	0,95	0,95
FCET 700 bar	0,53	0,54	0,55	0,56	0,58	0,59	0,59	0,60
FCET LH_2	1,49	1,50	1,50	1,50	1,51	1,51	1,51	1,52
BET	2,30	2,30	2,30	2,30	2,30	2,30	2,30	2,30
Rigid 6x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,76	0,76	0,77	0,77	0,78	0,78	0,79	0,79
FCET 700 bar	0,53	0,54	0,55	0,56	0,56	0,57	0,57	0,57
FCET LH_2	1,12	1,12	1,12	1,12	1,13	1,13	1,13	1,13
BET	1,66	1,66	1,66	1,66	1,66	1,66	1,66	1,66
Rigid 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,71	0,71	0,71	0,72	0,72	0,72	0,72	0,72
FCET 700 bar	0,58	0,58	0,58	0,59	0,59	0,59	0,60	0,60
FCET LH_2	0,92	0,92	0,92	0,92	0,92	0,92	0,93	0,93
BET	1,25	1,25	1,25	1,25	1,25	1,25	1,25	1,25

In addition to the previous payload gain, there is another one due to legislative: EU states that the payload for alternative powertrains can be increased compared to Diesel powertrains

[9]. The EU Directive stipulates that the increase can be from 1 to 2 tonnes, so this value can be chosen according to the case study. The model uses 2 tonnes:

Table 2.45 Payload gain due to regulation

Payload gain due to regulation [t]								
Tractor 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET 700 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET LH_2	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
BET	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
Rigid 6x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET 700 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET LH_2	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
BET	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
Rigid 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET 700 bar	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
FCET LH_2	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
BET	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00

Concerning payload losses, they are mainly due to batteries: small battery for FCET and large battery for BET. This component depends on battery capacity and battery density according to (2.14):

$$payload\ loss\ due\ to\ battery = -\frac{battery\ capacity}{battery\ density} \cdot \frac{1}{1000} \tag{2.14}$$

where the factor $\frac{1}{1000}$ is only used to convert from kilogram to tonnes.

In the following tables are summarised all the values used in the model for the TCO evaluation:

Table 2.46 Payload loss due to small battery

Payload loss due to small battery [t]								
Tractor 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	- 0,90	- 0,90	- 0,90	- 0,85	- 0,80	- 0,76	- 0,72	- 0,69
FCET 700 bar	- 0,90	- 0,90	- 0,90	- 0,85	- 0,80	- 0,76	- 0,72	- 0,69
FCET LH_2	- 0,90	- 0,90	- 0,90	- 0,85	- 0,80	- 0,76	- 0,72	- 0,69
BET	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Rigid 6x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	- 0,81	- 0,81	- 0,81	- 0,76	- 0,72	- 0,68	- 0,64	- 0,61
FCET 700 bar	- 0,81	- 0,81	- 0,81	- 0,76	- 0,72	- 0,68	- 0,64	- 0,61
FCET LH_2	- 0,81	- 0,81	- 0,81	- 0,76	- 0,72	- 0,68	- 0,64	- 0,61
BET	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Rigid 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	- 0,75	- 0,75	- 0,75	- 0,71	- 0,67	- 0,63	- 0,60	- 0,57
FCET 700 bar	- 0,75	- 0,75	- 0,75	- 0,71	- 0,67	- 0,63	- 0,60	- 0,57
FCET LH_2	- 0,75	- 0,75	- 0,75	- 0,71	- 0,67	-0,63	- 0,60	- 0,57
BET	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 2.47 Payload loss due to large battery

Payload loss due to large battery [t]								
Tractor 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 700 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET LH_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
BET	- 8,14	- 8,09	- 8,05	- 7,53	- 7,03	- 6,63	- 6,23	- 5,90
Rigid 6x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 700 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET LH_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
BET	- 4,48	- 4,45	- 4,42	- 4,13	- 3,86	- 3,63	- 3,41	- 3,22
Rigid 4x2								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 350 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET 700 bar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
FCET LH_2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
BET	- 2,64	- 2,62	- 2,60	- 2,43	- 2,27	- 2,13	- 2,00	- 1,89

Once all the reductions/increases are assessed, the gross payloads are calculated as the sum of the standard payloads and reductions/increases (Table 2.48):

Table 2.48 Gross payload

Gross payload [t]								
Tractor 4x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	27,00	27,00	27,00	27,00	27,00	27,00	27,00	27,00
FCET 350 bar	29,00	29,01	29,02	29,08	29,13	29,18	29,23	29,26
FCET 700 bar	28,63	28,64	28,65	28,71	28,78	28,83	28,87	28,91
FCET LH_2	29,59	29,60	29,60	29,65	29,71	29,75	29,79	29,83
BET	23,16	23,21	23,25	23,77	24,27	24,67	25,07	25,40
Rigid 6x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	14,50	14,50	14,50	14,50	14,50	14,50	14,50	14,50
FCET 350 bar	16,45	16,45	16,46	16,51	16,56	16,60	16,65	16,68
FCET 700 bar	16,22	16,23	16,24	16,30	16,34	16,39	16,43	16,46
FCET LH_2	16,81	16,81	16,81	16,86	16,91	16,95	16,99	17,02
BET	13,68	13,71	13,74	14,03	14,30	14,53	14,75	14,94
Rigid 4x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	10,50	10,50	10,50	10,50	10,50	10,50	10,50	10,50
FCET 350 bar	12,46	12,46	12,46	12,51	12,55	12,59	12,62	12,65
FCET 700 bar	12,33	12,33	12,33	12,38	12,42	12,46	12,50	12,53
FCET LH_2	12,67	12,67	12,67	12,71	12,75	12,79	12,83	12,86
BET	11,11	11,13	11,15	11,32	11,48	11,62	11,75	11,86

The last step is to apply two correction factors:

- *Average loading factor*, it is used to reflect the actual situation of the truck routes. It is assumed equal to 90% for tractor 4x2, 80% for rigid 6x2, and 70% for rigid 4x2;
- *Share of empty runs*, it is used to consider that part of the route is covered with empty truck and it is different for each country (Table 2.49) [36]:

Table 2.49 Share of empty runs

Share of empty runs [%]	
Albania	20,0 %
Croatia	27,0 %
Czechia	17,0 %
France	18,0 %
Germany	23,0 %
Greece	31,0 %
Hungary	23,0 %
Ireland	34,0 %
Italy	20,0 %
Norway	29,0 %
Poland	23,0 %
Portugal	21,0 %
Slovakia	23,0 %
Spain	25,0 %
United Kingdom	20,0 %

With these assumptions, the net payload is calculated. For simplicity, the results shown in Table 2.50 are for the selection of Italy as country:

Table 2.50 Net payload

Net payload [t]								
Tractor 4x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	19,44	19,44	19,44	19,44	19,44	19,44	19,44	19,44
FCET 350 bar	20,88	20,88	20,89	20,94	20,97	21,01	21,05	21,07
FCET 700 bar	20,61	20,62	20,63	20,67	20,72	20,76	20,79	20,82
FCET LH_2	21,30	21,31	21,31	21,35	21,39	21,42	21,45	21,48
BET	16,68	16,71	16,74	17,12	17,47	17,76	18,05	18,29
Rigid 6x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	9,28	9,28	9,28	9,28	9,28	9,28	9,28	9,28
FCET 350 bar	10,53	10,53	10,54	10,57	10,60	10,62	10,65	10,67
FCET 700 bar	10,38	10,39	10,39	10,43	10,46	10,49	10,51	10,53
FCET LH_2	10,76	10,76	10,76	10,79	10,82	10,85	10,87	10,89
BET	8,75	8,77	8,79	8,98	9,16	9,30	9,44	9,56
Rigid 4x2								
	2023	2024	2025	2026	2027	2028	2029	2030
Diesel	5,88	5,88	5,88	5,88	5,88	5,88	5,88	5,88
FCET 350 bar	6,98	6,98	6,98	7,01	7,03	7,05	7,07	7,08
FCET 700 bar	6,90	6,90	6,90	6,93	6,96	6,98	7,00	7,02
FCET LH_2	7,09	7,09	7,09	7,12	7,14	7,16	7,19	7,20
BET	6,22	6,23	6,24	6,34	6,43	6,51	6,58	6,64

Now that all input parameters have been set, the model returns the outputs.

2.2 Outputs

The objective of the model is to evaluate the TCO of a truck in order to compare different powertrains. To do this, all TCO components are calculated separately to compare which is the most significant contribution.

The TCO can be divided into different contributions according to the technology:

- *Chassis*, for all technologies;
- *Powertrain and other components*, Diesel powertrain for Diesel trucks, E-Drive powertrain, Fuel Cell, hydrogen tank, and small battery for FCET, and large battery for BET;
- *Energy/Fuel*, Diesel for conventional trucks, hydrogen for FCET, and electrical energy for BET;
- *Registration fee*, for all technologies;
- *Motor vehicle tax*, for all technologies;
- *Insurance*, for all technologies;
- *Maintenance*, for all technologies;

- *Infrastructure*, for all technologies;
- *Road toll*, for all technologies;
- *Residual value*, for all technologies.

2.2.1 Chassis

The chassis cost is an input parameter, so no calculation is needed to evaluate it. The costs of these components are reported in Table 2.22.

2.2.2 Powertrains and other components

- **Diesel truck**

Conventional trucks are equipped with only one component, the diesel powertrain, so its evaluation is easier than other technologies because the powertrain cost is an input parameter (Table 2.23).

- **FCET**

Fuel Cell Electric Trucks are composed by different components including E-Drive powertrain, FC module, H_2 tank, and small battery. The cost of the first three components are reported in dedicated tables, separately for tractor 4x2, rigid 6x2, and rigid 4x2. The cost of small battery is calculated multiplying the battery capacity (Table 2.39) with the specific cost of the battery (Table 2.4):

$$small\ battery\ cost = capacity \cdot specific\ cost \tag{2.15}$$

- **BET**

Regarding BET, the only powertrain is the large battery, so like for the small battery, the cost is calculated multiplying the battery capacity (Table 2.37) with the specific cost of the battery (Table 2.2):

$$large\ battery\ cost = capacity \cdot specific\ cost \tag{2.16}$$

Since all these components have a limited life, it is necessary to take into account whether more components are needed along the life of the truck. If the truck's overall mileage is longer than the life of the component, a replacement is required, so the cost related to that component increases.

2.2.3 Energy/Fuel

The energy/fuel cost depends on the truck type: for Diesel truck is given by the sum of Diesel and Ad-Blue cost, for FCET is given by the H_2 cost, and for BET is given by the electrical energy cost.

The Diesel cost is obtained by:

$$Diesel\ cost = consumption \cdot annual\ mileage \cdot years \cdot specific\ cost \tag{2.17}$$

The Ad-Blue cost is obtained by:

$$Ad - Blue = consumption \cdot annual\ mileage \cdot years \cdot specific\ cost \tag{2.18}$$

The H_2 cost is obtained by:

$$H_2\ cost = consumption \cdot annual\ mileage \cdot years \cdot specific\ cost \tag{2.19}$$

The electrical energy cost is obtained by:

$$energy\ cost = consumption \cdot annual\ mileage \cdot years \cdot specific\ cost \tag{2.20}$$

2.2.4 Registration fee

The registration fee is fixed for all technologies and typologies according to Table 2.8.

2.2.5 Motor vehicle tax

This tax is fixed as the registration fee, so it depends on the country according to Table 2.7.

2.2.6 Insurance

Insurance is evaluated as a percentage of the total vehicle cost:

- *Diesel truck*, chassis (Table 2.22) and diesel powertrain (Table 2.23) are considered:

$$insurance = insurance\ \% \cdot (chassis + powertrain) \cdot years \tag{2.21}$$

- *FCET*, chassis (Table 2.22), E-Drive powertrain (Table 2.24 - Table 2.26), FC module (Table 2.28 - Table 2.30), H_2 tank (Table 2.33 - Table 2.35), and small battery (2.15) are considered:

$$insurance = insurance\ \% \cdot (chassis + powertrain + FC + \\ + H_2\ tank + small\ battery) \cdot years \tag{2.22}$$

- BET, chassis (Table 2.22) and large battery (2.16) are considered:

$$insurance = insurance\ \% \cdot (chassis + large\ battery) \cdot years \tag{2.23}$$

2.2.7 Maintenance

The total maintenance cost is given by the product of maintenance cost (Table 2.6), different for each technology, annual mileage (Table 2.18), and number of years:

$$total\ maintenance\ cost = maintenance\ cost \cdot annual\ mileage \cdot years \tag{2.24}$$

2.2.8 Road toll

The road toll is paid every year, so it is calculated multiplying the road toll tax with the annual mileage and the lifetime of the truck:

$$total\ road\ toll = road\ toll\ tax \cdot annual\ mileage \cdot years \tag{2.25}$$

2.2.9 Residual value

This cost component is one of the most difficult to evaluate because it takes into account several aspects, such as the scrap value, if one or more components are used, the lifetime of components, and if the total mileage of the truck is higher or lower than the lifetime of the components.

The base form of the equations used to calculate the residual value is the following:

$$residual\ value = \frac{component}{N} \cdot (N-1) \cdot scrap\ value + \frac{component}{N} \cdot \Big[1 + \\ -(1 - scrap\ value) \cdot \frac{years \cdot annual\ mileage - (N-1) \cdot lifetime}{lifetime}\Big] \tag{2.26}$$

where N is the number of components used during the total life of the truck.

Obviously, the equation is adapted according to the technologies because each truck type has different components with a residual value: Diesel truck and BET have only one component included in the evaluation, Diesel powertrain and large battery respectively, whereas FCET has more than one component, like E-Drive powertrain, FC module, H_2 tank, and small battery.

3. Results

The model returns three different results:

- *TCO in €/truck*, which directly reflects the total cost of the truck throughout its life;
- *TCO in c€/t-km*, which reflects the cost of transporting 1 t payload on 1 km of route;
- *CO_2 emissions in gCO_2/t-km*, which reflects the CO_2 emissions of transporting 1 t payload on 1 km of route.

Although the input parameters in the previous chapter are reported from 2023 to 2030, TCO analysis is carried out until 2040. Most parameters are considered constant from 2030 to 2040, whereas other parameters change every year from 2023 to 2040 (even if for simplicity they are not reported). Then, each output is given for each year, from 2023 to 2040, and it is divided into two time periods: the 1st life and the 1st and 2nd life combined.

3.1 TCO in €/truck

The first output that is analysed is the TCO in €/truck (1st and 2nd life combined) that immediately gives an idea of the overall cost of the truck throughout its life. In order not to make reading too heavy with a long series of numerical results, in order to analyse the results only some specific years are considered, in particular 2023, 2027, and 2030. The TCO is first broken down into its components to better analysed how this cost is composed, then it is analysed its overall value in order to compare the different technologies. The first technology analysed is the Diesel truck, the conventional technology assumed as base case (Table 3.1):

Table 3.1 TCO for Diesel truck [€/truck]

Diesel truck [€/truck]									
	Tractor 4x2			Rigid 6x2			Rigid 4x2		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	58.100	58.100	58.100	54.600	54.600	54.600
Diesel powertrain	24.000	26.500	26.500	19.500	21.550	21.550	17.500	19.325	19.325
Diesel consumption	905.941	923.826	936.064	503.424	510.720	515.394	299.184	302.976	305.316
Ad-Blue consumption	17.233	16.841	16.547	9.576	9.310	9.111	5.691	5.523	5.397
Registration fee	101	101	101	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	13.050	13.425	13.425	11.640	11.948	11.948	10.815	11.089	11.089
Maintenance	168.000	168.000	168.000	114.000	114.000	114.000	72.000	72.000	72.000
Infrastructure	0	0	0	0	0	0	0	0	0
Road toll	112.000	112.000	112.000	76.000	76.000	76.000	48.000	48.000	48.000
Residual value	2.400	2.650	2.650	7.591	8.389	8.389	10.750	11.871	11.871
TCO	**1.307.475**	**1.327.593**	**1.339.537**	**791.300**	**799.890**	**804.364**	**503.692**	**508.293**	**510.507**

By looking the three different typologies, one for each route, it is obvious that the cost per truck decreases with an annual mileage reduction. It is possible to see that in the three main items which depend on the mileage: Diesel consumption, maintenance, and road toll.

Analysing the three typology at one specific year (e.g., 2023) is evident that three are the main components of the TCO: again, Diesel consumption, maintenance cost, and road toll. For all the technologies, only these three components account from 80% to 91% of the TCO and the most important contribute is due to the Diesel consumption cost with more than half of the total TCO (from 57% to 69%).

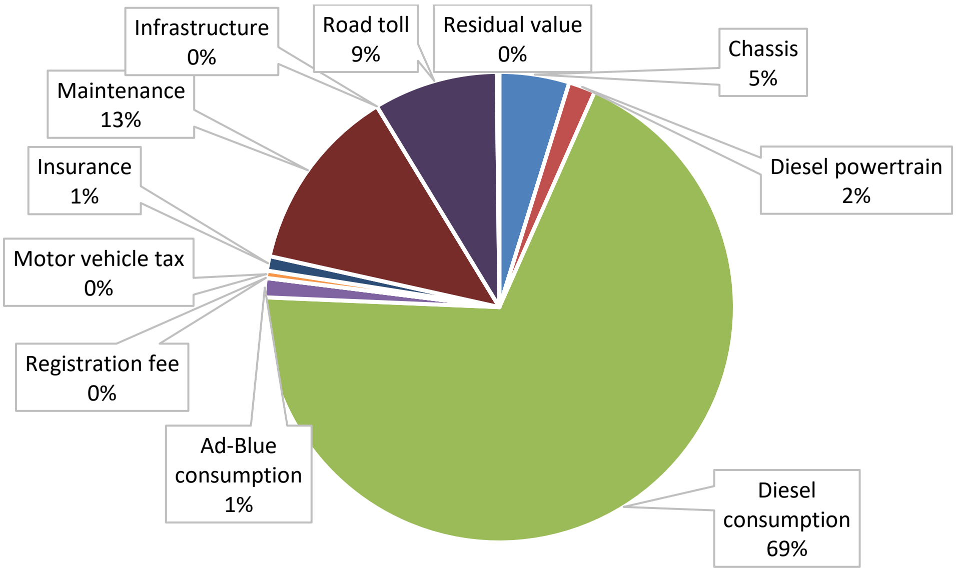

Figure 3.1 Composition of TCO for Diesel tractor 4x2 (2023)

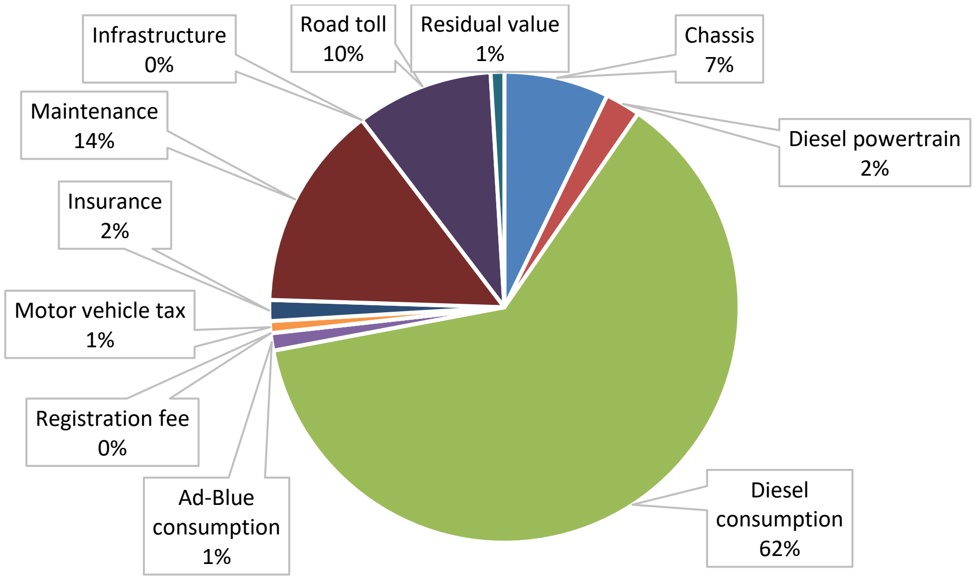

Figure 3.2 Composition of TCO for Diesel rigid 6x2 (2023)

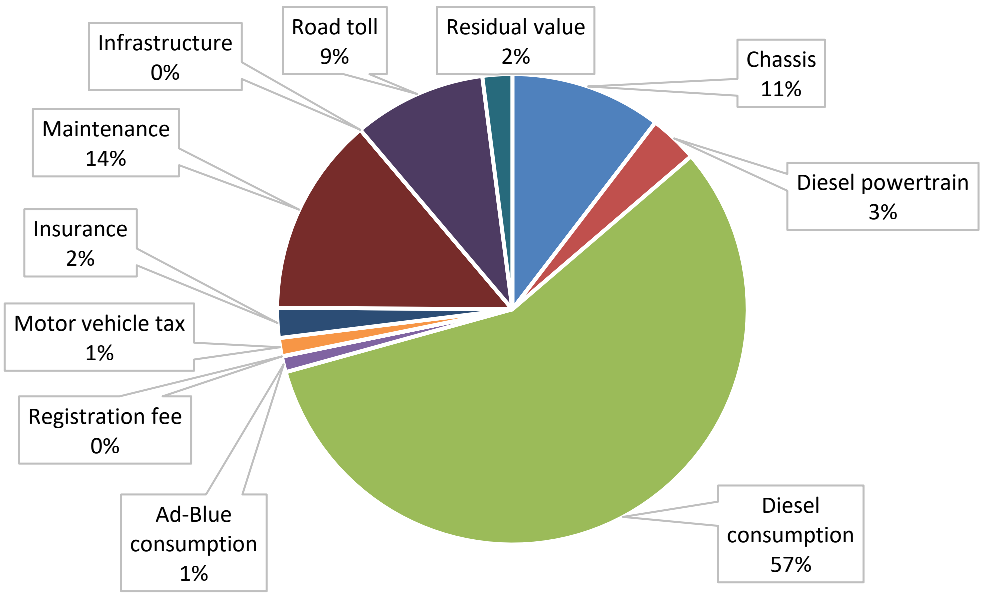

Figure 3.3 Composition of TCO for Diesel rigid 4x2 (2023)

Regarding the FCET, it is possible to note that the TCO tends to decrease over years thanks to the improvements in technology and efficiency of components and to the market evolution: in 2023 the maturity of technology is set to "niche", so the prices of components are high, whereas in 2030 the market maturity is set to "rather mass", so the prices are lower. This effect is evident in the FC module cost, where in 2030 the cost is about one third of the cost in 2023.

In the following table and figures is possible to see how the components affect the total TCO:

Table 3.2 TCO for FCET 350 bar [€/truck]

FCET 350 bar [€/truck]									
	Tractor 4x2			Rigid 6x2			Rigid 4x2		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	58.100	58.100	58.100	54.600	54.600	54.600
E-Drive powertrain	37.401	19.650	18.871	34.341	17.636	16.999	31.791	15.957	15.438
FC module	103.200	44.880	37.200	77.400	33.660	27.900	51.600	22.440	18.600
H_2 tank	60.497	39.162	34.359	33.329	21.464	18.756	19.620	12.613	11.005
Small battery	46.389	33.390	32.625	41.496	29.868	29.184	38.584	27.772	27.136
H_2 consumption	890.366	682.219	557.558	490.530	373.921	304.360	288.756	219.718	178.591
Registration fee	101	101	101	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	46.573	30.012	27.908	36.700	24.109	22.641	29.429	20.007	19.017
Maintenance	154.000	154.000	154.000	104.500	104.500	104.500	66.000	66.000	66.000
Infrastructure	0	0	0	0	0	0	0	0	0
Road toll	112.000	112.000	112.000	76.000	76.000	76.000	48.000	48.000	48.000
Residual value	18.699	9.792	8.870	70.366	38.471	34.890	86.139	47.854	43.916
TCO	**1.501.378**	**1.175.172**	**1.035.303**	**888.682**	**707.414**	**630.222**	**548.893**	**445.904**	**401.171**

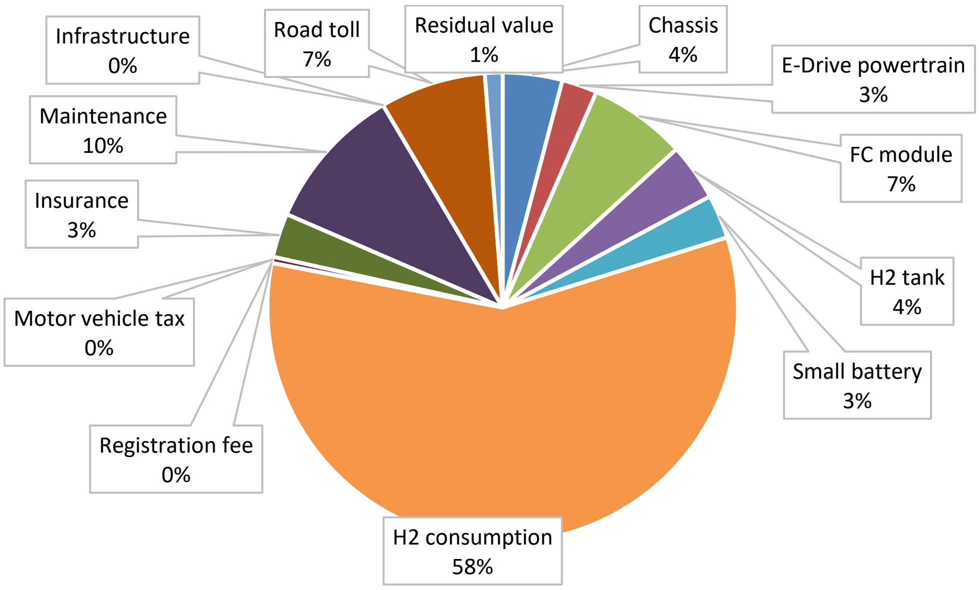

Figure 3.4 Composition of TCO for FCET 350 bar tractor 4x2 (2023)

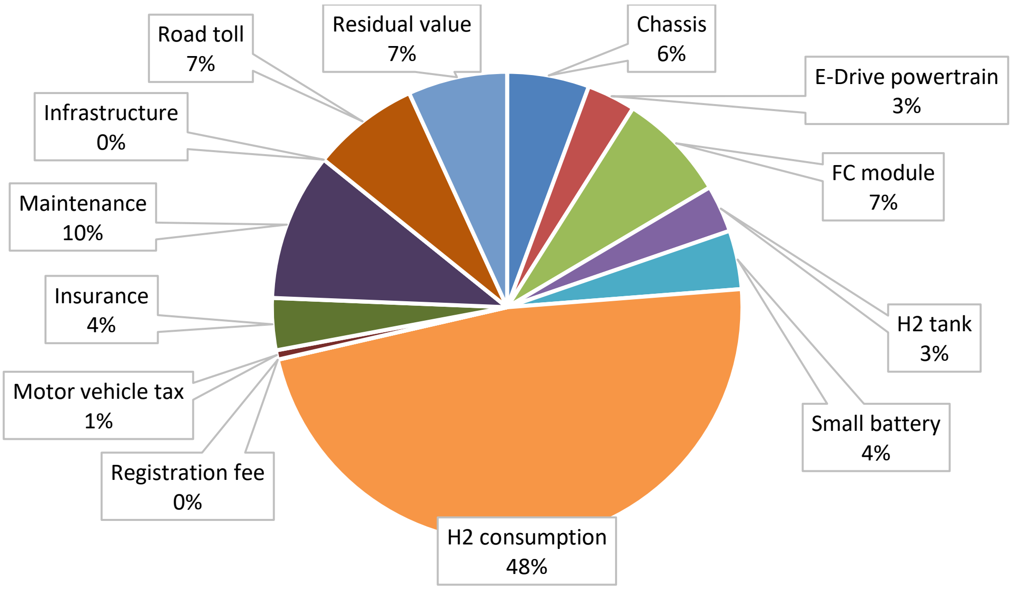

Figure 3.5 Composition of TCO for FCET 350 bar rigid 6x2 (2023)

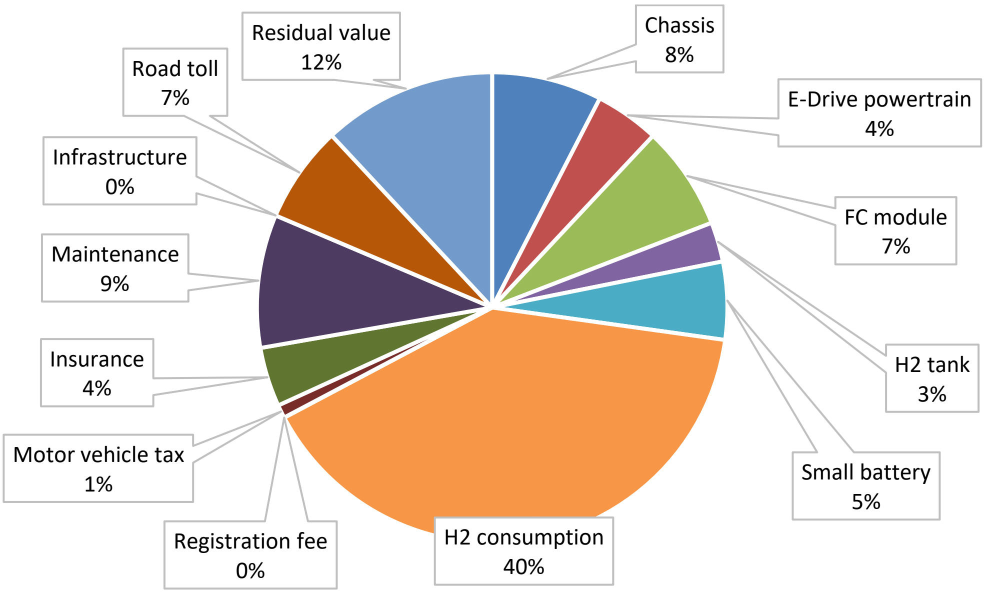

Figure 3.6 Composition of TCO for FCET 350 bar rigid 4x2 (2023)

For short and mid-haul segments, in which the annual mileage is lower than the lifetime of the single component, the residual value plays an important role. This is mainly due to two causes: the reduction in annual mileage done from the truck, as said before, and the increasing in the cost of components with respect to the Diesel truck. In this way, the residual value affects about 12% of the TCO for the case of rigid 4x2 truck with an annual mileage of 60.000 km. For all typologies of trucks, the most important contribute is given by the H_2 consumption, with a value higher than 40% of the TCO. This contribution is more important for long-haul segment than for short-haul segment.

The next technology to analysed is the FCET at 700 bar: the trend is similar to the trend of FCET at 350 bar, where the only small differences are related to the fuel consumption cost and H_2 tank.

Table 3.3 TCO for FCET 700 bar [€/truck]

FCET 700 bar [€/truck]									
	Tractor 4x2			Rigid 6x2			Rigid 4x2		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	58.100	58.100	58.100	54.600	54.600	54.600
E-Drive powertrain	37.401	19.650	18.871	34.341	17.636	16.999	31.791	15.957	15.438
FC module	103.200	44.880	37.200	77.400	33.660	27.900	51.600	22.440	18.600
H_2 tank	65.474	42.013	37.572	36.071	23.027	20.510	21.234	13.531	12.035
Small battery	46.389	33.390	32.625	41.496	29.184	29.184	38.584	27.772	27.136
H_2 consumption	941.982	725.094	594.729	518.967	397.420	324.650	305.496	233.527	190.497
Registration fee	101	101	101	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	47.320	30.440	28.390	37.111	24.344	22.904	29.671	20.145	19.171
Maintenance	154.000	154.000	154.000	104.500	104.500	104.500	66.000	66.000	66.000
Infrastructure	0	0	0	0	0	0	0	0	0
Road toll	112.000	112.000	112.000	76.000	76.000	76.000	48.000	48.000	48.000
Residual value	18.699	9.792	8.870	71.247	38.971	35.456	87.061	48.379	44.509
TCO	**1.558.717**	**1.221.326**	**1.076.168**	**919.390**	**732.209**	**651.966**	**566.566**	**460.244**	**413.673**

The composition of the TCO is reported in the following figures:

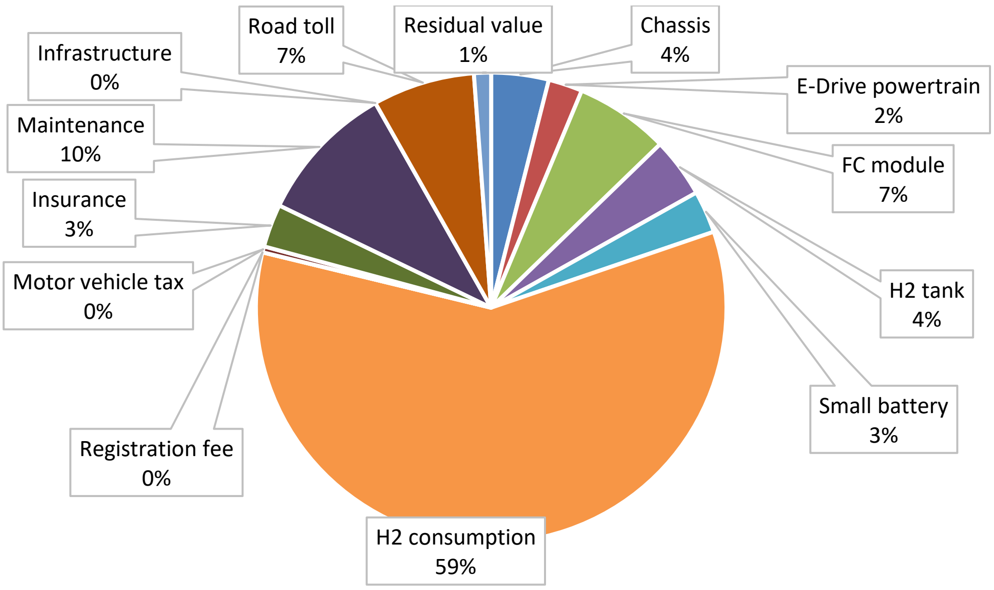

Figure 3.7 Composition of TCO for FCET 700 bar tractor 4x2 (2023)

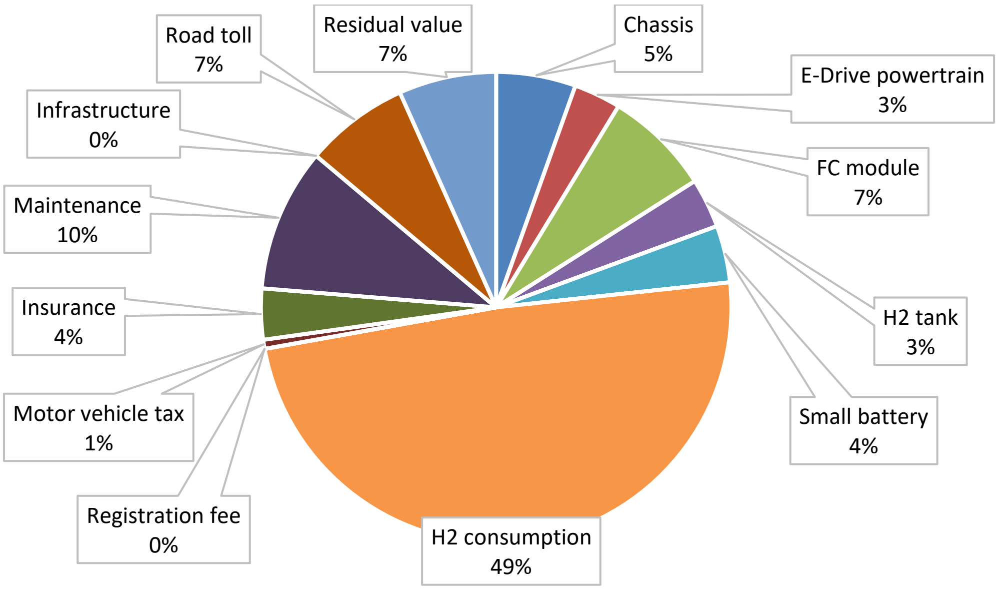

Figure 3.8 Composition of TCO for FCET 700 bar rigid 6x2 (2023)

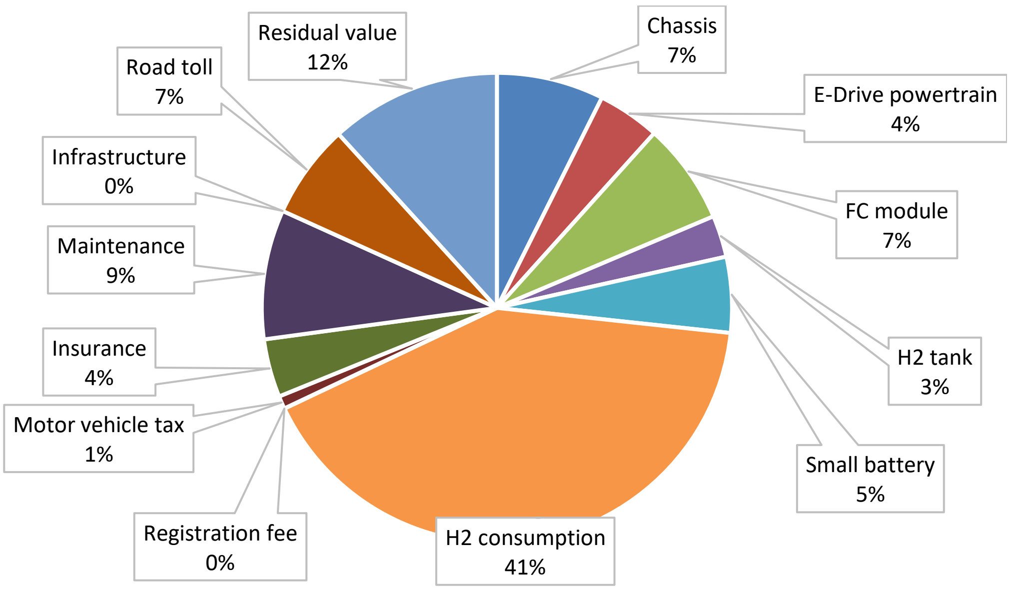

Figure 3.9 Composition of TCO for FCET 700 bar rigid 4x2 (2023)

The last FCET technology is the one powered by LH_2. In this case, the fuel consumption is higher with respect to the other two typologies, but the H_2 tank is cheaper. In general, the trend is almost the same as before, then the same comments done for FCET at 350 bar are valid also for this typology.

Table 3.4 TCO for FCET LH_2 [€/truck]

FCET LH_2 [€/truck]									
	Tractor 4x2			Rigid 6x2			Rigid 4x2		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	58.100	58.100	58.100	54.600	54.600	54.600
E-Drive powertrain	37.401	19.650	18.871	34.341	17.636	16.999	31.791	15.957	15.438
FC module	103.200	44.880	37.200	77.400	33.660	27.900	51.600	22.440	18.600
H_2 tank	31.578	16.352	13.513	17.397	8.963	7.376	10.241	5.267	4.328
Small battery	46.389	33.390	32.625	41.496	29.868	29.184	38.584	27.772	27.136
H_2 consumption	993.597	741.487	594.729	547.403	406.405	324.650	322.235	238.807	190.497
Registration fee	101	101	101	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	42.235	26.591	24.781	34.310	22.234	20.934	28.022	18.905	18.015
Maintenance	154.000	154.000	154.000	104.500	104.500	104.500	66.000	66.000	66.000
Infrastructure	0	0	0	0	0	0	0	0	0
Road toll	112.000	112.000	112.000	76.000	76.000	76.000	48.000	48.000	48.000
Residual value	18.699	9.792	8.870	65.245	34.477	31.210	80.780	43.656	40.052
TCO	**1.571.353**	**1.208.210**	**1.048.500**	**932.354**	**729.540**	**641.084**	**576.945**	**460.742**	**409.214**

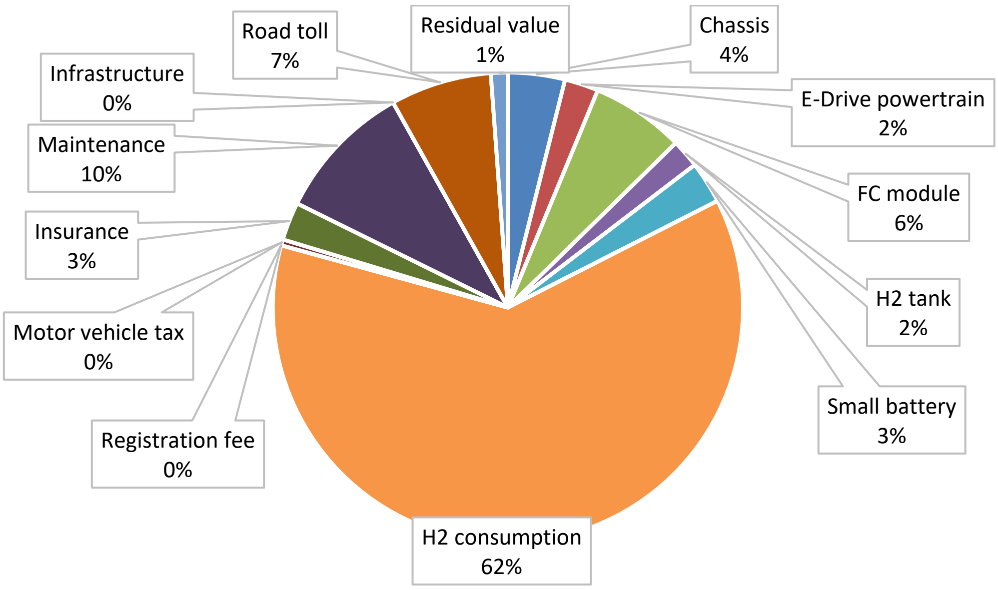

Figure 3.10 Composition of TCO for FCET LH_2 tractor 4x2 (2023)

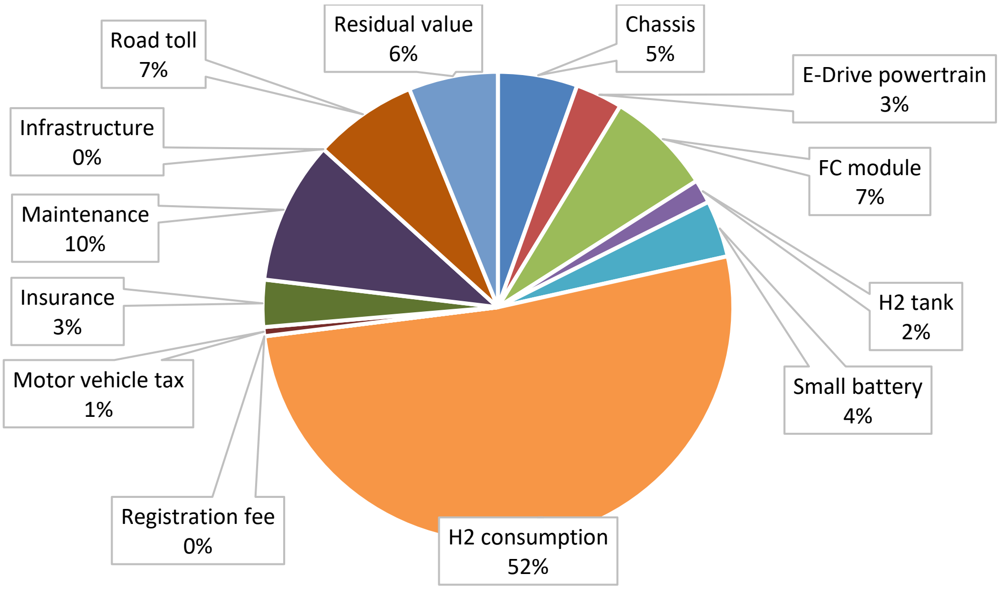

Figure 3.11 Composition of TCO for FCET LH_2 rigid 6x2 (2023)

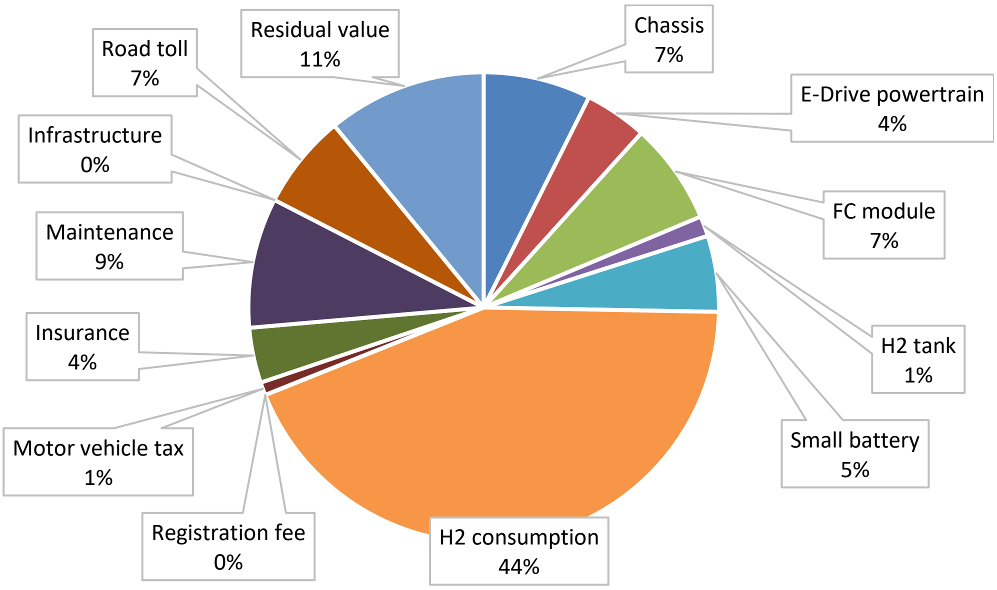

Figure 3.12 Composition of TCO for FCET LH_2 rigid 4x2 (2023)

The last technology is the BET, in which the main powertrain is the large battery and the "fuel" is the electrical energy. In this case, the composition of the TCO is slightly different because the most important contribute is due to the cost of the large battery, especially when the market is not a mass market (with a cost of around 31-40% of the TCO). According to the lifetime of the powertrain, it is necessary to use more than one battery during all the life of the truck and this increments the cost. Consequently, by using more than one battery, the second one at the end of the truck life is almost new, so its residual value is high enough, mainly for short and mid-haul segment (between 13% and 19% of TCO), as it is possible to see from Table 3.5:

Table 3.5 TCO for BET [€/truck]

BET [€/truck]									
	Tractor 4x2			Rigid 6x2			Rigid 4x2		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	58.100	58.100	58.100	54.600	54.600	54.600
Large battery	802.104	565.498	541.872	441.904	309.946	295.797	260.132	182.127	173.566
Energy consumption	644.548	503.909	412.593	355.101	276.190	225.226	209.034	162.291	132.157
Registration fee	101	101	101	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	129.766	94.275	90.731	75.001	55.207	53.085	47.210	35.509	34.225
Maintenance	154.000	154.000	154.000	104.500	104.500	104.500	66.000	66.000	66.000
Infrastructure	0	0	0	0	0	0	0	0	0
Road toll	112.000	112.000	112.000	76.000	76.000	76.000	48.000	48.000	48.000
Residual value	80.210	56.550	54.187	172.027	120.658	115.150	159.795	111.878	106.619
TCO	**1.831.858**	**1.442.782**	**1.326.660**	**945.230**	**765.937**	**704.209**	**531.832**	**443.300**	**408.580**

The composition of the TCO for the three different typologies of BET, for 2023, is reported in the following figures:

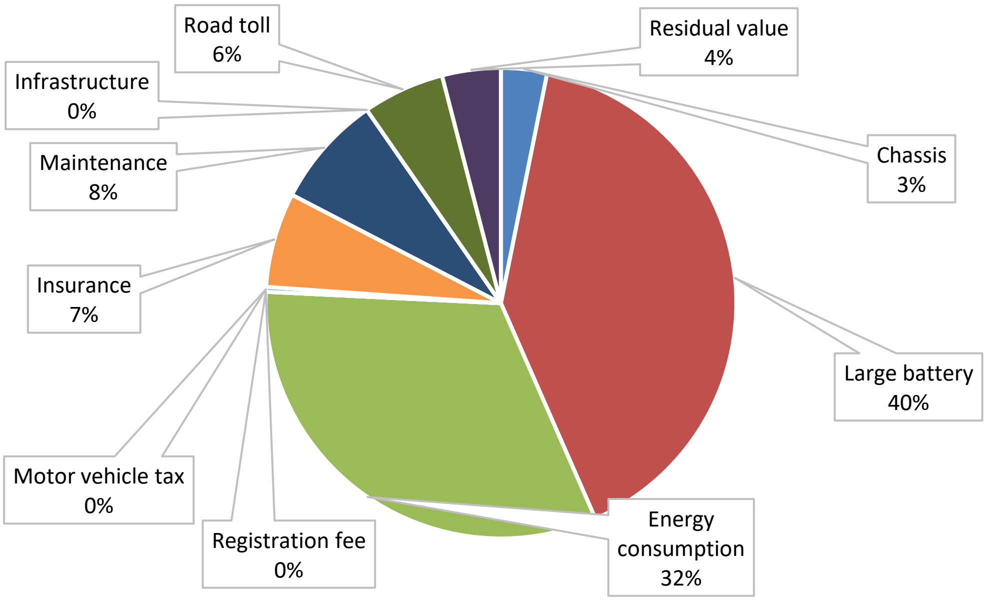

Figure 3.13 Composition of TCO for BET tractor 4x2 (2023)

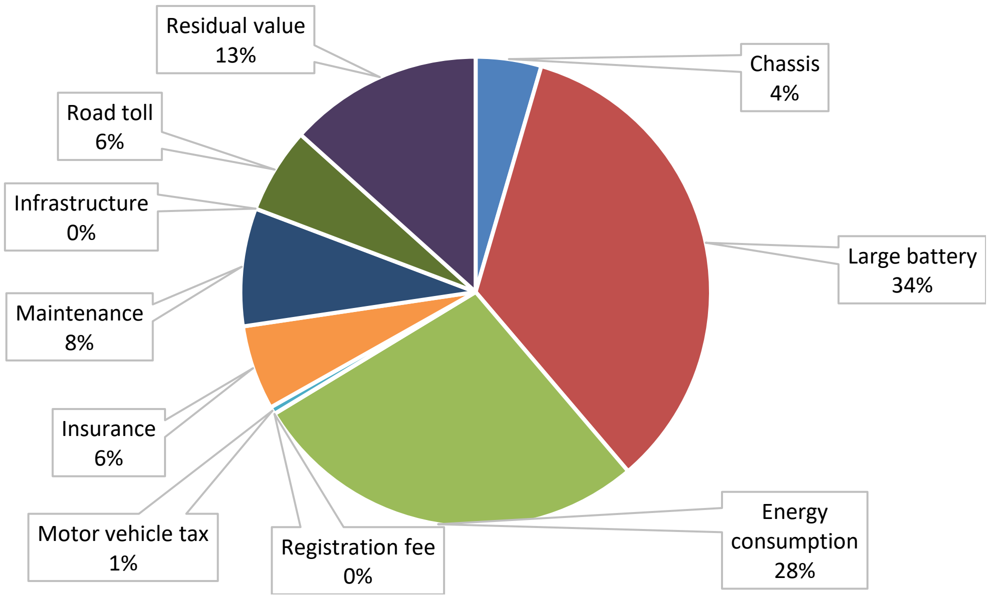

Figure 3.14 Composition of TCO for BET rigid 6x2 (2023)

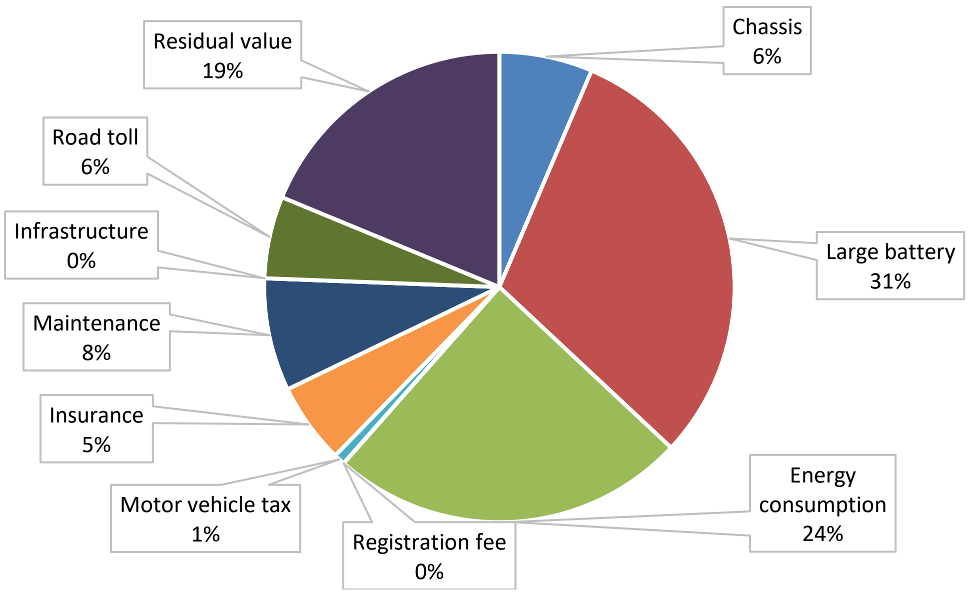

Figure 3.15 Composition of TCO for BET rigid 4x2 (2023)

In the previous figures and tables has been seen in detail how the TCO is composed, analysing each component in term of percentage of the total to compare which one is the most significant. The next step is to analyse the general trend of the TCO over the years, in order to see if and how it will reduce. This analysis is important in order to understand which technology has the best probability to build a stable and sustainable market in the future, going towards the goals of low emissions in the transport sector in terms of both sustainability and economy, so let's separately consider the three truck types.

- **Tractor 4x2**

The TCO results, from 2023 to 2040, for 1st and 2nd life combined, are reported in Table 3.6:

Table 3.6 TCO of tractor 4x2 [€/truck]

TCO of tractor 4x2 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	1.307.475	1.501.378	1.558.717	1.571.353	1.831.858
2024	1.312.016	1.433.565	1.487.914	1.492.085	1.796.059
2025	1.319.071	1.370.677	1.422.066	1.417.966	1.739.332
2026	1.323.388	**1.311.647**	1.361.375	1.349.003	1.707.237
2027	1.327.593	1.175.172	**1.221.326**	**1.208.210**	1.442.782
2028	1.331.686	1.125.880	1.169.450	1.151.779	1.409.676
2029	1.335.667	1.078.322	1.121.828	1.097.163	1.359.036
2030	1.339.537	1.035.303	1.076.168	1.048.500	**1.326.660**
2031	1.339.537	997.768	1.037.687	1.015.040	1.211.134
2032	1.339.537	997.232	1.037.150	1.014.694	1.211.134
2033	1.339.537	996.601	1.036.614	1.014.347	1.211.134
2034	1.339.537	996.065	1.035.983	1.014.000	1.211.134
2035	1.339.537	968.801	1.007.867	992.611	1.141.818
2036	1.339.537	968.611	1.007.582	992.516	1.141.818
2037	1.339.537	968.075	1.007.141	992.170	1.141.818
2038	1.339.537	967.886	1.006.951	992.075	1.141.818
2039	1.339.537	967.444	1.006.415	991.823	1.141.818
2040	1.339.537	967.255	1.006.226	991.728	1.141.818

From the data in the table above, it is possible to note an important difference between FCET and BET: for this truck typology (tractor 4x2 with high annual mileage), TCO of BET is always higher than the TCO of FCET and it reaches the target (TCO lower than the one of Diesel engine) after 7 years (2030), whereas for FCET all typologies reach a TCO lower than the Diesel truck TCO in around 3-4 years (2026-2027). To analyse the trends, some considerations can be made taking into account percentage terms. To simplify the analysis without loss information, only a few years are considered, such as 2023, 2027, 2030, 2034, 2037, and 2040:

Table 3.7 Percentage variation in TCO (tractor 4x2) [€/truck]

Percentage variation in TCO (tractor 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	1,54 %	2,45 %	2,45 %	2,45 %	2,45 %
FCET 350 bar	0,00 %	- 21,73 %	- 31,04 %	- 33,66 %	- 35,52 %	- 35,58 %
FCET 700 bar	0,00 %	- 21,65 %	- 30,96 %	- 33,54 %	- 35,39 %	- 35,45 %
FCET LH_2	0,00 %	- 23,11 %	- 33,27 %	- 35,47 %	- 36,86 %	- 36,89 %
BET	0,00 %	- 21,24 %	- 27,58 %	- 33,88 %	- 37,67 %	- 37,67 %

Table 3.7 shows the variation in percentage terms of the TCO over years. With the assumptions made by this model (no additional taxes for Diesel truck and no incentives for alternative powertrains), the increase in Diesel trucks TCO is very small until 2040, whereas for all the other technologies the reduction is important, especially in the next 7 years from now.

Among alternative powertrains, BET has the slowest reduction in the first 7 years, but in 2040 is the technology with the highest TCO reduction.

In the previous analysis, percentage variations among the same technology have been considered. Another consideration is the variation year by year between the different technologies in order to see, at a specific year, which technology is better with respect to Diesel engine:

Table 3.8 Percentage variation in TCO with respect to Diesel truck (tractor 4x2)

Percentage variation in TCO with respect to Diesel truck (tractor 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	14,83 %	- 11,48 %	- 22,71 %	- 25,64 %	- 27,73 %	- 27,79 %
FCET 700 bar	19,22 %	- 8,00 %	- 19,66 %	- 22,66 %	- 24,81 %	- 24,88 %
FCET LH_2	20,18 %	- 8,99 %	- 21,73 %	- 24,30 %	- 25,93 %	- 25,96 %
BET	40,11 %	8,68 %	- 0,96 %	- 9,59 %	- 14,76 %	- 14,76 %

This analysis is probable the most significative because it immediately provides information about how far a specific technology is from the goal of balancing the TCO of Diesel truck. In particular, Table 3.8 shows that the situation at 2023 is that TCO of FCETs are about 15-20% higher than that one of Diesel trucks, whereas for BET the situation is worst: it is 40% higher than Diesel powertrain. Considering 4 years later, in 2027, the gap between FCETs and Diesel trucks is reduced and FCETs have reached the target with a reduction of about 8-12%, whereas for BET the TCO is still 8,68% higher. In 2030 it is possible to see that all technologies have reached the goal and they all have a TCO lower than the Diesel powertrain (around -20% for FCETs and -1% for BETs). The last consideration can be done at 2040 in which the best technology is the FCET at 350 with a reduction of 27,79% with respect to the TCO of conventional trucks.

All these considerations, particularly the last, can be seen most simply in Figure 3.16:

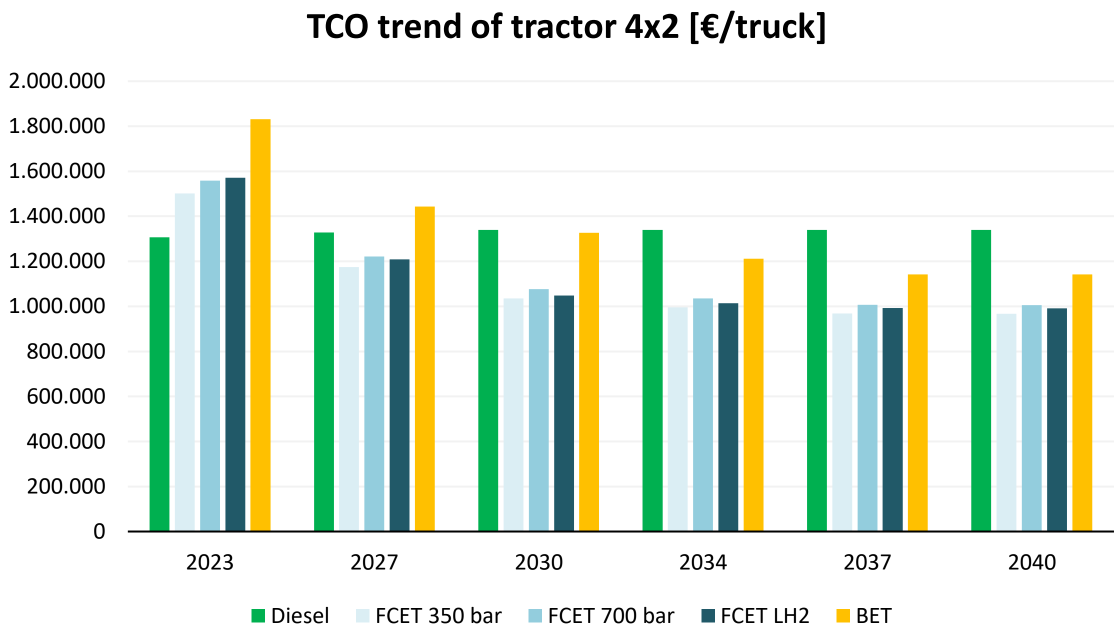

Figure 3.16 TCO trend of tractor 4x2 [€/truck]

- **Rigid 6x2**

In Table 3.9 are reported the results from 2023 to 2040 for the TCO of rigid 6x2 trucks:

Table 3.9 TCO of rigid 6x2 [€/truck]

TCO of rigid 6x2 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	791.300	888.682	919.390	932.354	945.230
2024	793.172	851.169	880.213	888.379	926.290
2025	796.527	816.404	843.805	847.276	895.876
2026	798.246	**783.819**	810.293	809.097	878.590
2027	799.890	707.414	**732.209**	**729.540**	**765.937**
2028	801.457	680.173	703.494	698.251	748.536
2029	802.949	653.938	677.166	668.023	721.141
2030	804.364	630.222	651.966	641.084	704.209
2031	804.364	609.540	630.911	622.005	658.521
2032	804.364	609.291	630.663	621.830	658.521
2033	804.364	609.005	630.414	621.656	658.521
2034	804.364	608.757	630.128	621.482	658.521
2035	804.364	594.358	615.394	609.394	631.107
2036	804.364	594.284	615.283	609.357	631.107
2037	804.364	594.035	615.071	609.183	631.107
2038	804.364	593.961	614.997	609.146	631.107
2039	804.364	593.749	614.748	609.009	631.107
2040	804.364	593.675	614.673	608.972	631.107

Analysing these data, the most important differences with respect to the previous typology (tractor 4x2) are two: the TCO values are lower due to the lower annual mileage, that is the main reason of the increase of TCO, and that BETs reduce the gap with the other technologies achieving the target in a short time.

All technologies reach the target in about 3-4 years, for FCET at 350 bar, FCET at 700 bar, and FCET LH_2 the number of years needed to get a lower TCO that the TCO of conventional trucks is the same, whereas the only technology with a remarkable improvement is BET that reaches the goal in 4 years with respect to the 7 years of the previous typology.

To better understand these data and to better analysed the trends, as done before, some considerations in terms of percentage values are needed:

Table 3.10 Percentage variation in TCO (rigid 6x2) [€/truck]

Percentage variation in TCO (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00%	1,09 %	1,65 %	1,65 %	1,65 %	1,65 %
FCET 350 bar	0,00%	- 20,40 %	- 29,08 %	- 31,50 %	- 33,16 %	- 33,20 %
FCET 700 bar	0,00%	- 20,36 %	- 29,09 %	- 31,46 %	- 33,10 %	- 33,14 %
FCET LH_2	0,00%	- 21,75 %	- 31,24 %	- 33,34 %	- 34,66 %	- 34,68 %
BET	0,00%	- 18,97 %	- 25,50 %	- 30,33 %	- 33,23 %	- 33,23 %

The table above shows the variation of the TCO, as a percentage value, with respect to 2023. Conventional trucks increase is very low, as for trucks with high annual mileage, whereas for other technologies the reduction is significant, but lower with respect to the tractor 4x2 typology (Table 3.7). Also looking at the different technologies, with mid-haul segment, so with truck rigid 6x2, the one with the highest percentage reduction is the FCET LH_2 with around 35% of reduction in 2040 with respect to 2023. FCETs at 350 and 700 bar have approximately the same reduction (-33%), a little bit lower than tractor 4x2. BET has the lowest reduction, together with FCET at 350 and 700 bar, in contrast to the previous typology in which it is the best one.

The last consideration take into account percentage variation for the different technologies at the same year, similarly to what done for tractor 4x2:

Table 3.11 Percentage variation in TCO with respect to Diesel truck (rigid 6x2)

Percentage variation in TCO with respect to Diesel truck (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	12,31 %	- 11,56 %	- 21,65 %	- 24,32 %	- 26,15 %	- 26,19 %
FCET 700 bar	16,19 %	- 8,46 %	- 18,95 %	- 21,66 %	- 23,53 %	- 23,58 %
FCET LH_2	17,83 %	- 8,79 %	- 20,30 %	- 22,74 %	- 24,27 %	- 24,29 %
BET	19,45 %	- 4,24 %	- 12,45 %	- 18,13 %	- 21,54 %	- 21,54 %

Table 3.11 shows the most significant aspect of this analysis, namely shows how at a specific year the TCO of a specific technology is with respect to the TCO of conventional Diesel

truck. In 2023, no technology is comparable to Diesel engine because the TCO is about 12-20% higher, but just 4 years later, in 2027, this gap is entirely reduced for all technologies with a TCO of 4-12% lower than the TCO of conventional trucks. In 2040, when the model forecast ends, all technologies are competitive with respect to Diesel trucks, but the best one, as for the previous typology, remains FCETs at 350 bar.

To summarise these considerations, Figure 3.17 gives an overview of the evolution of the different technologies over the years of interest in the study:

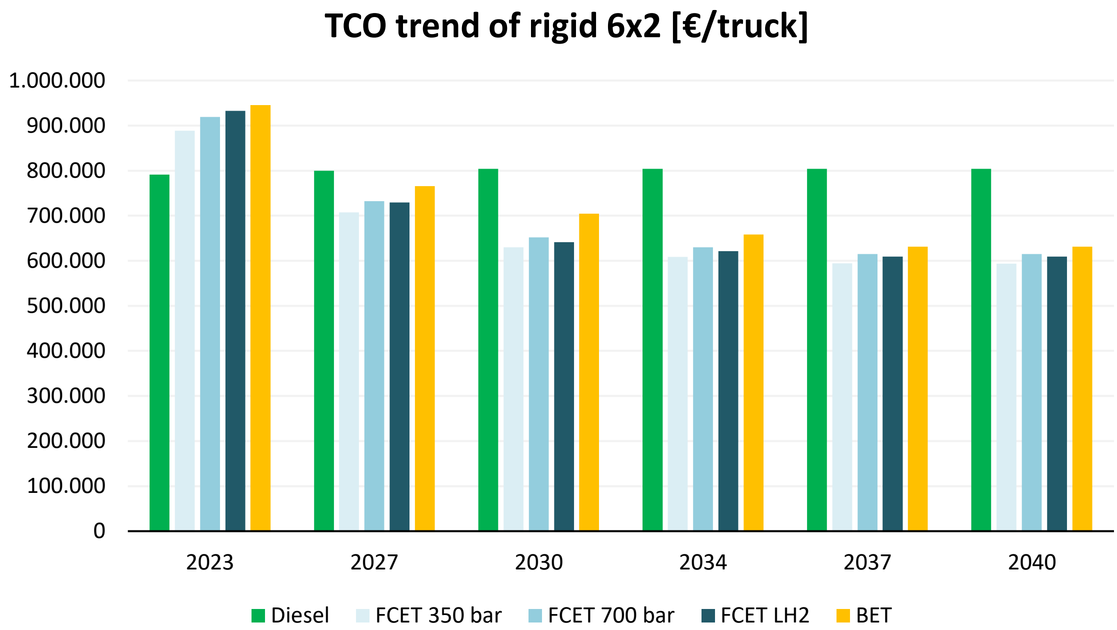

Figure 3.17 TCO trend of rigid 6x2 [€/truck]

- **Rigid 4x2**

Table 3.12 summarises the TCO results for all years and for all technologies, according to the assumptions above mentioned:

Table 3.12 TCO of rigid 4x2 [€/truck]

TCO of rigid 4x2 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	503.692	548.893	566.566	576.945	531.832
2024	504.670	527.317	544.013	551.504	521.356
2025	506.577	507.326	523.058	527.718	**504.133**
2026	507.459	**488.594**	**503.783**	**505.638**	494.431
2027	508.293	445.904	460.244	460.742	443.300
2028	509.079	430.104	443.559	442.504	433.654
2029	509.817	414.904	428.288	424.902	417.943
2030	510.507	401.171	413.673	409.214	408.580
2031	510.507	389.901	402.250	398.601	389.701
2032	510.507	389.791	402.140	398.521	389.701
2033	510.507	389.666	402.030	398.442	389.701
2034	510.507	389.556	401.905	398.362	389.701
2035	510.507	382.042	394.253	391.795	378.373
2036	510.507	382.011	394.207	391.779	378.373
2037	510.507	381.901	394.112	391.700	378.373
2038	510.507	381.870	394.082	391.685	378.373
2039	510.507	381.776	393.972	391.620	378.373
2040	510.507	381.745	393.941	391.605	378.373

As for truck rigid 6x2, even in this case all technologies reach a TCO lower than the one of Diesel truck, and if FCET at 350 bar always takes 3 years to reach the goal (in 2026), FCET at 700 bar and FCET LH_2 take one year less to reach the goal, reaching it in 3 years as the FCET at 350 bar. The technology with the best improvement is BET that takes only 2 years to reach a TCO lower than the one of Diesel powertrain. This reduction in time is still due to the reduced annual mileage compared to other typologies (tractor 4x2 and rigid 6x2), and this affects all the main cost components, as seen in the first part of this chapter.

A further analysis regarding percentage variation of TCO is useful to better know the evolution of the market in the next years and to better understand which technology can be a serious competitor of Diesel trucks. Results are reported in Table 3.13:

Table 3.13 Percentage variation in TCO (rigid 4x2) [€/truck]

Percentage variation in TCO (rigid 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,91 %	1,35 %	1,35 %	1,35 %	1,35 %
FCET 350 bar	0,00 %	- 18,76 %	- 26,91 %	- 29,03 %	- 30,42 %	- 30,45 %
FCET 700 bar	0,00 %	- 18,77 %	- 26,99 %	- 29,06 %	- 30,44 %	- 30,47 %
FCET LH_2	0,00 %	- 20,14 %	- 29,07 %	- 30,95 %	- 32,11 %	- 32,12 %
BET	0,00 %	- 16,65 %	- 23,17 %	- 26,72 %	- 28,85 %	- 28,85 %

The diesel truck trend is almost the same as the other typologies, whereas for the other technologies (FCETs and BET) the reduction over years is slightly lower with respect to the long and mid-haul segment trucks. In 2040, FCET LH_2 has the highest reduction (-32,12%), whereas BET has the lowest reduction (-28,85%). FCET at 350 and 700 bar have the same TCO reduction, so their trends are basically the same.

Considering percentage variations year by year, the results are summarised in Table 3.14:

Table 3.14 Percentage variation in TCO with respect to Diesel truck (rigid 4x2)

Percentage variation in TCO with respect to Diesel truck (rigid 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	8,97 %	- 12,27 %	- 21,42 %	- 23,69 %	- 25,19 %	- 25,22 %
FCET 700 bar	12,48 %	- 9,45 %	- 18,97 %	- 21,27 %	- 22,80 %	- 22,83 %
FCET LH_2	14,54 %	- 9,35 %	- 19,84 %	- 21,97 %	- 23,27 %	- 23,29 %
BET	5,59 %	- 12,79 %	- 19,97 %	- 23,66 %	- 25,88 %	- 25,88 %

As for 2023, all technologies have a high TCO compared to the TCO of Diesel truck (about 9-15% for FCETs and about 6% for BET), and for this truck typology, short-haul segment, BET is the best technology. In 2026 all technologies have reached the target with a TCO lower than the one of conventional engine and in 2040 BET reaches a reduction higher than 25%, the highest among all technologies and typologies.

All these considerations are better shown in Figure 3.18, in which the trends are reported until 2040:

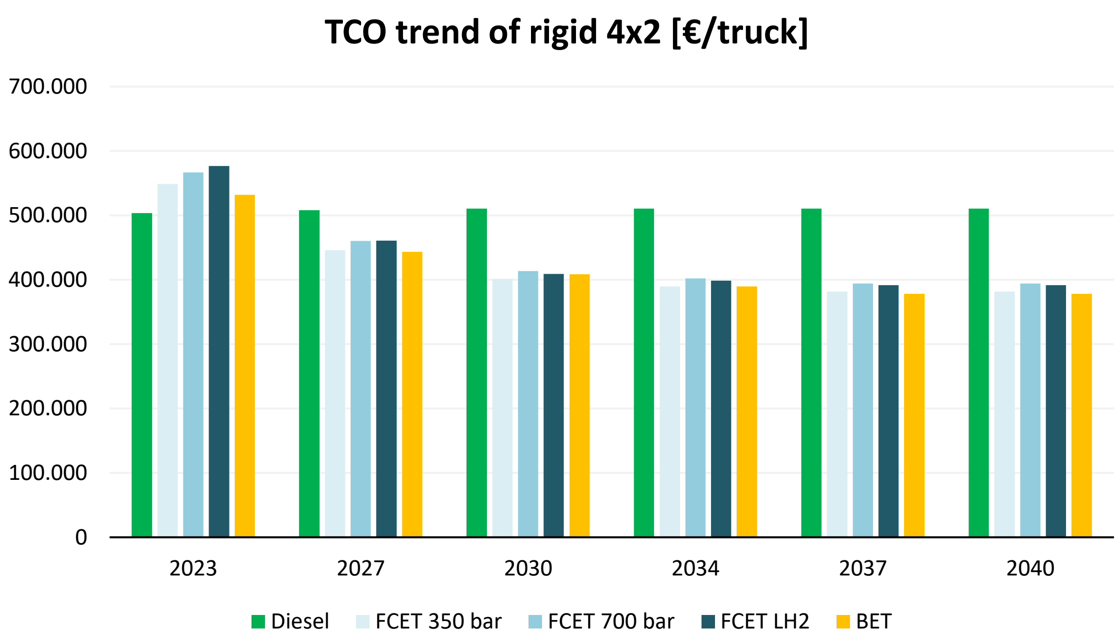

Figure 3.18 TCO trend of rigid 4x2 [€/truck]

- **Final considerations**

At the end of this analysis, it is important to highlight some points:

- FCETs always take 3-4 years to reach the target, independently from the typology of the truck;
- Among FCETs, the one at 700 bar is the worst solution for every typology, whereas the FCET at 350 bar is always the best one;
- For tractor 4x2, and so for long-haul segment, BET it is always the worst solution because it is the last one that reach the goal;
- For rigid 6x2, and so for mid-haul segment, all the alternative powertrains are comparable and they are all good competitors for Diesel trucks, even if FCET at 350 bar is slightly better than the others;
- For rigid 4x2, and so for short-haul segment, BET is the best alternative to conventional trucks, but all technologies are comparable.

3.2 TCO in c€/t-km

This second result obtained from the model reflects the cost of transporting one tonne payload on one kilometre of the route. It takes into account the weight-related factor that could impact the truck payload, such as the weight of the alternative powertrain or the weight of the batteries that could potentially reduce the weight of goods to be transported. This result is obtained according to the following equation:

$$TCO\left[{}^{c€}/_{t-km}\right] = \frac{TCO[€/truck] \cdot 100}{years \cdot annual\ mileage \cdot net\ payload} \tag{3.1}$$

where the factor 100 is to convert from € to c€, whereas the net payload is evaluated in tonnes.

Then, according to the results obtained for the TCO in €/truck (Table 3.6, Table 3.9, and Table 3.12) and to the net payload assumption (Table 2.50), the TCO in c€/t-km is evaluated for the three different typologies and for all technologies.

- **Tractor 4x2**

Table 3.15 TCO of tractor 4x2 [c€/t-km]

TCO of tractor 4x2 [c€/t-km]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	4,80	5,14	5,40	5,27	7,85
2024	4,82	4,90	5,15	5,00	7,68
2025	4,85	**4,69**	4,92	**4,75**	7,42
2026	4,86	4,47	**4,70**	4,51	7,12
2027	4,88	4,00	4,21	4,03	5,90
2028	4,89	3,83	4,02	3,84	5,67
2029	4,91	3,66	3,85	3,65	5,38
2030	4,92	3,51	3,69	3,49	5,18
2031	4,92	3,38	3,56	3,38	**4,73**
2032	4,92	3,38	3,56	3,37	4,73
2033	4,92	3,38	3,56	3,37	4,73
2034	4,92	3,38	3,55	3,37	4,73
2035	4,92	3,28	3,46	3,30	4,46
2036	4,92	3,28	3,46	3,30	4,46
2037	4,92	3,28	3,46	3,30	4,46
2038	4,92	3,28	3,45	3,30	4,46
2039	4,92	3,28	3,45	3,30	4,46
2040	4,92	3,28	3,45	3,30	4,46

The same considerations done for the TCO in €/truck can be done for these results: for long-haul segment, BET solution is less competitive with respect to the other alternative powertrains reaching the goal in 8 years (in 2031). FCETs are competitive in about 2 years for FCET at 350 bar and for FCET LH_2, whereas for FCET at 700 bar the competitiveness starts from 2026 (3 years).

Considering percentage variations of these values with respect to 2023, the situation until 2040 is reported in Table 3.16:

Table 3.16 Percentage variation in TCO (tractor 4x2) [c€/t-km]

Percentage variation in TCO (tractor 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	1,54 %	2,45 %	2,45 %	2,45 %	2,45 %
FCET 350 bar	0,00 %	- 22,08 %	- 31,68 %	- 34,27 %	- 36,11 %	- 36,17 %
FCET 700 bar	0,00 %	- 22,06 %	- 31,65 %	- 34,20 %	- 36,03 %	- 36,09 %
FCET LH_2	0,00 %	- 23,43 %	- 33,83 %	- 36,01 %	- 37,39 %	- 37,41 %
BET	0,00 %	- 24,82 %	- 33,95 %	- 39,70 %	- 43,16 %	- 43,16 %

The data reflect the trend of the TCO in €/truck, so the increase value in Diesel truck is very low (about 2%), whereas all the other technologies have an important reduction especially in the first period (from 2023 to 2030). The fuel cell technologies have a similar trend with a final reduction in 2040 equal to around 36% of the TCO in 2023, whereas BETs are the best one in term of reduction (-43,16% in 2040).

Considering percentage variations year by year, FCET at 350 bar and FCET LH_2 have almost the same evolution, as reported in the following table:

Table 3.17 Percentage variation in TCO with respect to Diesel truck (tractor 4x2)

Percentage variation in TCO with respect to Diesel truck (tractor 4x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	6,93 %	- 17,95 %	- 28,69 %	- 31,40 %	- 33,32 %	- 33,38 %
FCET 700 bar	12,44 %	- 13,69 %	- 24,98 %	- 27,78 %	- 29,79 %	- 29,86 %
FCET LH_2	9,68 %	- 17,29 %	- 29,16 %	- 31,49 %	- 32,97 %	- 33,00 %
BET	63,32 %	20,92 %	5,29 %	- 3,88 %	- 9,38 %	- 9,38 %

These data show that the best technologies as competitor for conventional trucks are FCET at 350 bar and FCET LH_2, with a reduction higher than 33% with respect to the TCO of Diesel engine trucks in 2040. FCET at 700 bar has a little gap with the other technologies that does not allow to be competitive like the other two FCET typologies. Finally, for long-haul segment BETs are not competitive as the other technologies without other incentives.

- **Rigid 6x2**

Table 3.18 TCO of rigid 6x2 [c€/t-km]

TCO of rigid 6x2 [c€/t-km]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	8,98	**8,88**	9,32	9,12	11,37
2024	9,00	8,51	**8,92**	**8,69**	11,11
2025	9,04	8,16	8,55	8,29	10,73
2026	9,05	7,81	8,18	7,89	10,30
2027	9,07	7,02	7,37	7,09	**8,81**
2028	9,09	6,74	7,06	6,77	8,47
2029	9,11	6,46	6,78	6,47	8,04
2030	9,12	6,22	6,52	6,20	7,75
2031	9,12	6,01	6,31	6,01	7,25
2032	9,12	6,01	6,30	6,01	7,25
2033	9,12	6,01	6,30	6,01	7,25
2034	9,12	6,00	6,30	6,01	7,25
2035	9,12	5,86	6,15	5,89	6,95
2036	9,12	5,86	6,15	5,89	6,95
2037	9,12	5,86	6,15	5,89	6,95
2038	9,12	5,86	6,15	5,89	6,95
2039	9,12	5,86	6,14	5,89	6,95
2040	9,12	5,85	6,14	5,89	6,95

With respect to the previous typology, in this case the number of years necessary to achieve the goal of a TCO lower than the one of Diesel trucks is lower for all technologies. Particularly, with FCET at 350 bar it is possible to see how this technology is competitive just in 2023. For the other FCET technologies the target is reached in one year (2024), whereas for BETs 4 years are necessary (2027). In 2040 all technologies are competitive, but the best one is FCET at 350 bar followed by FCET LH_2.

Analysing percentage variations of these values with respect to 2023, the results are summarised in Table 3.19:

Table 3.19 Percentage variation in TCO (rigid 6x2) [c€/t-km]

Percentage variation in TCO (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	1,09 %	1,65 %	1,65 %	1,65 %	1,65 %
FCET 350 bar	0,00 %	- 20,93 %	- 30,04 %	- 32,43 %	- 34,06 %	- 34,10 %
FCET 700 bar	0,00 %	- 20,95 %	- 30,10 %	- 32,44 %	- 34,06 %	- 34,10 %
FCET LH_2	0,00 %	- 22,22 %	- 32,07 %	- 34,15 %	- 35,45 %	- 35,47 %
BET	0,00 %	- 22,53 %	- 31,79 %	- 36,22 %	- 38,87 %	- 38,87 %

These results are similar to the results obtained for the TCO in €/truck, namely the BET is the solution with the highest reduction with respect to 2023 (around 39%), whereas the FCET LH_2 is the second one in terms of percentage reduction (35,47%).

Evaluating percentage variations of TCO with respect to conventional engine it is possible to do the main considerations in terms of competitiveness of the technology in the future:

Table 3.20 Percentage variation in TCO with respect to Diesel truck (rigid 6x2)

Percentage variation in TCO with respect to Diesel truck (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	- 1,02 %	- 22,58 %	- 31,88 %	- 34,20 %	- 35,79 %	- 35,83 %
FCET 700 bar	3,86 %	- 18,78 %	- 28,59 %	- 30,98 %	- 32,63 %	- 32,67 %
FCET LH_2	1,63 %	- 21,81 %	- 32,09 %	- 34,16 %	- 35,47 %	- 35,49 %
BET	26,65 %	- 2,94 %	- 15,02 %	- 20,53 %	- 23,84 %	- 23,84 %

Table 3.21 shows how all technologies reach the target, even if the reduction of the TCO of BET is smaller than the reductions of the other powertrains. FCETs have a similar trend, especially FCET at 350 bar and FCET LH_2, with the highest percentage reductions.

These results and these evolutions follow the same trends as the TCO in €/truck, so the considerations are very similar to what seen in the previous sections.

- **Rigid 4x2**

The results for this typology are reported in the following table:

Table 3.21 TCO of rigid 4x2 [c€/t-km]

TCO of rigid 4x2 [c€/t-km]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	14,28	**13,11**	**13,68**	**13,55**	**14,25**
2024	14,30	12,60	13,13	12,96	13,94
2025	14,36	12,12	12,63	12,40	13,46
2026	14,38	11,62	12,11	11,84	13,00
2027	14,41	10,57	11,03	10,75	11,49
2028	14,43	10,17	10,60	10,30	11,11
2029	14,45	9,78	10,20	9,86	10,59
2030	14,47	9,44	9,83	9,47	10,25
2031	14,47	9,17	9,55	9,22	9,78
2032	14,47	9,17	9,55	9,22	9,78
2033	14,47	9,17	9,55	9,22	9,78
2034	14,47	9,17	9,55	9,22	9,78
2035	14,47	8,99	9,36	9,07	9,50
2036	14,47	8,99	9,36	9,07	9,50
2037	14,47	8,98	9,36	9,07	9,50
2038	14,47	8,98	9,36	9,06	9,50
2039	14,47	8,98	9,36	9,06	9,50
2040	14,47	8,98	9,36	9,06	9,50

Differently from the previous cases, in the short-haul segment all technologies are competitive starting from 2023 in terms of c€/t-km.

A more detailed analysis on the percentage variations of the TCO is useful to better investigate which technology is the best one in terms of competitiveness:

Table 3.22 Percentage variation in TCO (rigid 4x2) [c€/t-km]

Percentage variation in TCO (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,91 %	1,35 %	1,35 %	1,35 %	1,35 %
FCET 350 bar	0,00 %	- 19,38 %	- 28,02 %	- 30,11 %	- 31,48 %	- 31,51 %
FCET 700 bar	0,00 %	- 19,39 %	- 28,16 %	- 30,21 %	- 31,56 %	- 31,59 %
FCET LH_2	0,00 %	- 20,67 %	- 30,13 %	- 31,98 %	- 33,12 %	- 33,14 %
BET	0,00 %	- 19,36 %	- 28,02 %	- 31,35 %	- 33,35 %	- 33,35 %

All technologies have almost the same evolution and in 2040 they all reach a reduction with respect to the value in 2023 of about 31-33%, whereas like in all the other cases previously analysed, Diesel trucks have a constant increase until 2040.

In Table 3.23 are reported, for some specific years between 2023 and 2040, the variations of TCO comparing Diesel trucks year by year. In this way it is possible to understand at the end of the analysed period which technology is the most competitive:

Table 3.23 Percentage variation in TCO with respect to Diesel truck (rigid 4x2)

Percentage variation in TCO with respect to Diesel truck (rigid 6x2)						
	2023	**2027**	**2030**	**2034**	**2037**	**2040**
Diesel truck	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %
FCET 350 bar	- 8,15 %	- 26,62 %	- 34,77 %	- 36,66 %	- 37,91 %	- 37,93 %
FCET 700 bar	- 4,20 %	- 23,47 %	- 32,10 %	- 34,03 %	- 35,31 %	- 35,34 %
FCET LH_2	- 5,06 %	- 25,37 %	- 34,55 %	- 36,29 %	- 37,35 %	- 37,37 %
BET	- 0,22 %	- 20,26 %	- 29,14 %	- 32,41 %	- 34,38 %	- 34,38 %

The values in the table above show that FCET at 350 bar and FCET LH_2 are always the best solutions, whereas FCET at 700 bar and BET have almost the same competitiveness with respect to conventional trucks.

- **Final considerations**

At the end of this analysis, it is important to point out some outcomes:

- FCET at 350 bar and FCET LH_2 have the same performances and they take a short time to reach the target (from 0 to 2 years), whereas FCET at 700 bar takes more time especially in long-haul segment truck, so it is always the worst solution among FCETs technologies;
- For tractor 4x2, and so for long-haul segment, BET reaches a TCO lower than the TCO of conventional trucks in more time with respect to the other technologies, so it is always the worst solution;
- For rigid 6x2, and so for mid-haul segment, all the FCET alternatives are comparable and they are all good competitors for Diesel trucks, whereas BETs are lagging behind other technologies;
- For rigid 4x2, and so for short-haul segment, all technologies are competitive compared to Diesel trucks just in 2023, even if BET and FCET at 700 bar are slightly worse than FCET at 350 bar and FCET LH_2 in 2040.

3.3 CO_2 emissions in gCO_2/t-km

The last outputs of the model is the CO_2 emissions of the truck in which is assumed that all the alternatives technologies are zero-carbon emissions, whereas only the conventional Diesel trucks are considered as CO_2 emitted trucks.

According to Table 2.15, in which are reported all the values of CO_2 emissions for the truck technology divided into “well to tank” and “tank to wheel”, and according to the following equation, the emissions in $gCO_2/t\text{-}km$ are calculated:

$$CO_2\ emissions = \frac{well\ to\ wheel\ CO_2\ emissions \cdot consumption}{net\ payload} \tag{3.2}$$

The results of this calculation are reported in Table 3.24:

Table 3.24 CO_2 emissions of conventional Diesel truck [$gCO_2/t\text{-}km$]

CO₂ emissions of conventional Diesel truck [gCO₂/t-km]			
	Tractor 4x2	**Rigid 6x2**	**Rigid 4x2**
2023	59,46	102,00	151,47
2024	59,12	101,29	150,35
2025	58,78	100,58	149,24
2026	58,44	99,87	148,12
2027	58,10	99,16	147,00
2028	57,77	98,45	145,88
2029	57,43	97,75	144,76
2030	57,09	97,04	143,65
2031	57,09	97,04	143,65
2032	57,09	97,04	143,65
2033	57,09	97,04	143,65
2034	57,09	97,04	143,65
2035	57,09	97,04	143,65
2036	57,09	97,04	143,65
2037	57,09	97,04	143,65
2038	57,09	97,04	143,65
2039	57,09	97,04	143,65
2040	57,09	97,04	143,65

These values depend on three parameters: the net payload of the truck (Table 2.50) whose value varies until 2030 and then is assumed constant, the fuel consumption of the truck (Table 2.42) whose value again varies until 2030 and then is assumed constant, and well to wheel CO_2 emissions (Table 2.15) that is a single value for each truck typology and for every year from 2023 to 2040 and it is obtained as the summation of the “well to tank” and “tank to wheel” emissions.

Based on these results, it is possible to do some considerations:

- CO_2 emissions increase with a reduction in the annual mileage of the truck, so tractor 4x2 has the lowest CO_2 emissions, whereas rigid 4x2 has the highest CO_2 emissions. For example, for mid-haul segment truck, the CO_2 emissions are 1,7 time higher than the emissions of tractor 4x2, and for rigid 4x2 they are 2,5 time higher than the one of long-haul segment truck;

- The trend until 2030 is a reduction in CO_2 emissions due to improvements in engine efficiency and then due to a reduction in fuel consumption, even if this emissions reduction is very low as reported in Table 3.25:

Table 3.25 Percentage variations in CO_2 emissions

Percentage variation in CO_2 emissions			
	2023	**2027**	**2030**
Tractor 4x2	0,00 %	- 2,29 %	- 3,99 %
Rigid 6x2	0,00 %	- 2,78 %	- 4,86 %
Rigid 4x2	0,00 %	- 2,95 %	- 5,16 %

4. Models comparison

Talking about TCO assessment models, one of the most used is the model proposed as a part of a study on fuel cells hydrogen trucks commissioned by Fuel Cell and Hydrogen Joint Undertaking and conducted by Roland Berger on 15 December 2020 (from now, it will be referred to as "RB model") [37]. The model described in the previous chapters (starting from now, for simplicity it will be called "This model") is an adjustment of RB model with respect to some parameters which have been updated. Hence, the same alternative powertrains of RB model have been analysed in "This model", but without considering the catenary truck technology, as it is not expected to have a great technological improvement in the short period. In this chapter, the main differences between the two models will be analysed, focusing on the results, in order to validate "This model" and to assess if it can be a useful tool.

The model comparison is divided into two main sections:

- The first is the comparison of the different contributes of single components (chassis cost, powertrain cost, etc.) for the three different typologies only in 2023;
- The second part is the comparison of the TCO, divided into 1st life and 1st and 2nd life combined, in three different years (2023, 2027, and 2030).

4.1 Comparison of individual components

The comparison of the two models by comparing each component of the TCO is done only for year 2023 because Roland Berger provides these data only for this specific year. The components are the same analysed in the previous chapter, but some of these are clustered, so the components are the following:

- Truck chassis cost;
- Powertrain cost, that includes powertrains (Diesel or E-Drive), FC module stack, hydrogen tank, and battery (small or large);
- Residual value;
- Energy/Fuel cost;
- Registration fee;
- Motor vehicle tax;
- Maintenance and insurance cost;
- Infrastructure cost;
- Road toll.

The comparison is done separately for each typology, so tractor 4x2, rigid 6x2, and rigid 4x2 are treated separately.

4.1.1 Tractor 4x2

The values obtained from "This model" and the values take from RB model are reported in Table 4.1 and Table 4.2:

Table 4.1 Comparison of tractor 4x2 ("This model")

"This model" TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	63.000	63.000	63.000	63.000	63.000
Powertrain cost	24.000	247.486	252.463	218.568	802.104
Residual value	2.400	18.699	18.699	18.699	80.210
Energy/Fuel cost	923.174	890.366	941.982	993.597	644.548
Registration fee	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550
Maintenance and insurance	181.050	200.573	201.320	196.235	283.766
Infrastructure cost	0	0	0	0	0
Road toll	112.000	112.000	112.000	112.000	112.000
TCO	**1.307.475**	**1.501.378**	**1.558.717**	**1.571.353**	**1.831.858**

Table 4.2 Comparison of tractor 4x2 (RB model)

RB model TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	63.000	63.000	63.000	63.000	63.000
Powertrain cost	24.000	239.000	243.000	214.000	631.000
Residual value	2.000	19.000	19.000	19.000	63.000
Energy/Fuel cost	612.000	601.000	639.000	655.000	445.000
Registration fee	0	0	0	0	0
Motor vehicle tax	8.000	28.000	28.000	25.000	41.000
Maintenance and insurance	173.000	169.000	170.000	168.000	161.000
Infrastructure cost	0	0	0	0	0
Road toll	238.000	238.000	238.000	238.000	238.000
TCO	**1.116.000**	**1.319.000**	**1.362.000**	**1.344.000**	**1.516.000**

Analysing these two tables containing the values for the two models, it is clear that the results are not the same, but they present some differences. The first difference that is easy to note is that the TCO of RB model are always lower than the results of "This model". Then, examining component by component, the differences are mainly due to energy/fuel cost and road toll for all technologies, whereas for BET also the powertrain, the maintenance and the insurance costs represent an important difference.

To better understand the entity of these differences, it is useful to calculate the percentage variations of "This model" with respect to RB model. The results are summarised in Table 4.3:

Table 4.3 Percentage variation between the two models (tractor 4x2)

Percentage variation between the two models (tractor 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
"This model" TCO [€/truck]	1.307.475 €	1.501.378 €	1.558.717 €	1.571.353 €	1.831.858 €
RB model TCO [€/truck]	1.116.000 €	1.319.000 €	1.362.000 €	1.344.000 €	1.516.000 €
ΔTCO [€/truck]	191.475 €	182.378 €	196.717 €	227.353 €	315.858 €
ΔTCO [%]	**17,16 %**	**13,83 %**	**14,44 %**	**16,92 %**	**20,83 %**

All the technologies present almost the same variation between the two models, an increase of around 14-21%. FCET at 350 bar is the technology with the lowest increase (13,83%), whereas BET is the one with the highest variation (20,83%).

4.1.2 Rigid 6x2

The TCO obtained from "This model" and the one evaluated by Roland Berger are reported in Table 4.4 and Table 4.5:

Table 4.4 Comparison of rigid 6x2 ("This model")

"This model" TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	58.100	58.100	58.100	58.100	58.100
Powertrain cost	19.500	186.566	189.308	170.634	441.904
Residual value	7.591	70.366	71.247	65.245	172.027
Energy/Fuel cost	513.000	490.530	518.967	547.403	355.101
Registration fee	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550
Maintenance and insurance	125.640	141.200	141.611	138.810	179.501
Infrastructure cost	0	0	0	0	0
Road toll	76.000	76.000	76.000	76.000	76.000
TCO	**791.300**	**888.682**	**919.390**	**932.354**	**945.230**

Table 4.5 Comparison of rigid 6x2 (RB model)

RB model TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	58.000	58.000	58.000	58.000	58.000
Powertrain cost	20.000	185.000	187.000	170.000	361.000
Residual value	8.000	70.000	71.000	65.000	109.000
Energy/Fuel cost	374.000	364.000	387.000	397.000	269.000
Registration fee	0	0	0	0	0
Motor vehicle tax	7.000	22.000	22.000	21.000	27.000
Maintenance and insurance	119.000	117.000	117.000	116.000	109.000
Infrastructure cost	0	0	0	0	0
Road toll	162.000	162.000	162.000	162.000	162.000
TCO	**732.000**	**838.000**	**862.000**	**859.000**	**877.000**

Comparing the values, it is possible to do the same considerations as the previous case, namely that the Roland Berger's estimation is always lower than the estimation of the model studied in the previous chapters. The most important differences between the two models are the same analysed for tractor 4x2, that is the energy/fuel cost and the road toll. In contrast to the previous analysis, in the mid-haul segment the differences in BET are decreasing, both for powertrain and for maintenance and insurance cost.

Evaluating the percentage variations of the two models is a good way to better understand if the models are comparable or if they provide completely different results. The percentage values are reported in Table 4.6:

Table 4.6 Percentage variation between the two models (rigid 6x2)

Percentage variation between the two models (rigid 6x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
“This model” TCO [€/truck]	791.300	888.682	919.390	932.354	945.230
RB model TCO [€/truck]	732.000	838.000	862.000	859.000	877.000
ΔTCO [€/truck]	59.300	50.682	57.390	73.354	68.230
ΔTCO [%]	**8,10 %**	**6,05 %**	**6,66 %**	**8,54 %**	**7,78 %**

With respect to the previous typology, the percentage variation is decreased from 7-12% to 6-9%, and BET technology is no more the worst: even if Diesel technology has a ΔTCO lower than the BET technology, the latter has a lower percentage increase.

4.1.3 Rigid 4x2

The results of the two models, component by component, are shown in the following tables in order to estimate the entity of the differences:

Table 4.7 Comparison of rigid 4x2 (“This model”)

“This model” TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	54.600	54.600	54.600	54.600	54.600
Powertrain cost	17.500	141.595	143.209	132.216	260.132
Residual value	10.750	86.139	87.061	80.780	159.795
Energy/Fuel cost	304.875	288.756	305.496	322.235	209.034
Registration fee	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550
Maintenance and insurance	82.815	95.429	95.671	94.022	113.210
Infrastructure cost	0	0	0	0	0
Road toll	48.000	48.000	48.000	48.000	48.000
TCO	**503.692**	**548.893**	**566.566**	**576.945**	**531.832**

Table 4.8 Comparison of rigid 4x2 (RB model)

RB model TCO components in 2023 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Chassis cost	55.000	55.000	55.000	55.000	55.000
Powertrain cost	18.000	141.000	142.000	132.000	155.000
Residual value	11.000	86.000	86.000	81.000	48.000
Energy/Fuel cost	222.000	214.000	228.000	233.000	159.000
Registration fee	0	0	0	0	0
Motor vehicle tax	7.000	18.000	18.000	17.000	19.000
Maintenance and insurance	76.000	77.000	77.000	76.000	70.000
Infrastructure cost	0	0	0	0	0
Road toll	102.000	102.000	102.000	102.000	102.000
TCO	**469.000**	**521.000**	**536.000**	**534.000**	**512.000**

Almost the same considerations as the previous cases can be done for rigid 4x2 trucks. The most important differences between the two models are the same analysed before, namely the energy/fuel cost and the road toll.

By estimating the percentage variations of "This model" with respect to RB model it is possible to better understand if the models work in a similar way or if they are based on different considerations:

Table 4.9 Percentage variation between the two models (rigid 4x2)

Percentage variation between the two models (rigid 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
"This model" TCO [€/truck]	503.692	548.892	566.566	576.945	531.832
RB model TCO [€/truck]	469.000	521.000	536.000	534.000	512.000
ΔTCO [€/truck]	34.692	27.892	30.566	42.945	19.832
ΔTCO [%]	**7,40 %**	**5,35 %**	**5,70 %**	**8,04 %**	**3,87 %**

Compared to the previous typologies, the percentage variation decreased from 7-12% to 4-8%, and BET technology is now the best both in terms of ΔTCO in €/truck and ΔTCO in percentage value.

Now that all three types of trucks have been analysed, it is possible to say that the reduction in the gap between the two models is a function of the annual mileage: the higher the annual mileage, the higher the difference between the two models. In fact, all the components that present a high difference between the models are function of the annual mileage (energy/fuel cost and road toll).

As conclusion it is possible to point out some aspects regarding the models:

- The models work differently for certain components, whereas for others work in a similar way;

- The models have a variation in the results ranging from 3,87% to 20,83%, so the majority of the results are comparable (except for tractor 4x2), therefore the "This model" works well;
- The components with the highest cost are related to the annual mileage, and they also are the components with the highest difference between the two models: this means that the difference in the results between the models is a function of the annual mileage, consequently if the annual mileage is low the two models give almost the same results.

4.2 Comparison in different years

The second part of the comparison between these two models does not take into account each component, but only the final result of the TCO in some specific years, in particular the years considered are 2023, 2027, and 2030, in which there are the most significant changes. The analysis is divided in 1st life and 1st and 2nd life combined and both are divided for each truck typology (tractor 4x2, rigid 6x2, and rigid 4x2).

Regarding the results of the RB model in 2023, they are not exactly the same as the previous analysis because in that case they were rounded to the nearest thousands, whereas in this analysis the values considered are the exact values that the model returns. Even for the years 2027 and 2030, TCO values are the exact values returned by the RB model.

With this premise can begin the analysis of the results of the 1st life.

4.2.1 1st life comparison in different years

The 1st life is composed by the first 5 years of life of the truck, so the results are lower with respect to the results reported until now because it was always considered the total life of the trucks (1st and 2nd life combined). Even in this analysis, the three types of trucks are studied separately.

4.2.1.1 Tractor 4x2

The first typology analysed is the one used for the long-haul segment with around 140.000 km/year, the results of which are shown in the following table:

Table 4.10 Comparison of the TCO of the models (tractor 4x2)

Comparison of the TCO of the models (tractor 4x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**"This model"**	685.288	782.240	810.909	817.227	917.401
	RB model	585.643	731.180	754.200	751.838	861.873
	Difference	99.645	51.060	56.709	65.389	55.528
		17,01 %	**6,98 %**	**7,52 %**	**8,70 %**	**6,44 %**
2027	**"This model"**	695.347	619.137	642.214	635.655	731.736
	RB model	584.985	595.041	613.471	603.547	695.503
	Difference	110.362	24.096	28.743	32.108	36.233
		18,87 %	**4,05 %**	**4,69 %**	**5,32 %**	**5,21 %**
2030	**"This model"**	701.319	549.202	569.635	555.801	674.560
	RB model	580.646	547.178	564.320	554.448	617.914
	Difference	120.673	2.024	5.315	1.353	56.646
		20,78 %	**0,37 %**	**0,94 %**	**0,24 %**	**9,17 %**

By looking and analysing the table above it is possible to see that the worst technology, in terms of difference in the results, is the conventional one, namely the Diesel engine trucks, whereas for all the other technologies the results are comparable. The TCO of Diesel trucks obtained from "This model" is always higher than the result of the model of Roland Berger and this difference is not negligible (17-21%), whereas for alternative powertrains the differences are low, especially in 2030. In 2023 BET has the best difference (6,44% higher), whereas in 2030 this difference increases until 9,17%. For FCETs, in 2030 the two models give almost the same results, with a difference lower than 1% (the best result obtained is for FCET LH_2 with a percentage difference of 0,24%).

4.2.1.2 Rigid 6x2

Concerning the mid-haul segment truck, the results obtained from the two models are:

Table 4.11 Comparison of the TCO of the models (rigid 6x2)

Comparison of the TCO of the models (rigid 6x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**"This model"**	424.751	473.441	488.796	507.949	485.144
	RB model	392.079	472.243	485.777	487.194	497.431
	Difference	32.672	1.198	3.019	20.755	- 12.287
		8,33 %	**0,25 %**	**0,62 %**	**4,26 %**	**- 2,47 %**
2027	**"This model"**	429.046	382.808	395.205	402.991	400.446
	RB model	391.879	392.500	403.421	399.550	414.342
	Difference	37.167	- 9.692	- 8.216	3.441	- 13.896
		9,48 %	**- 2,47 %**	**- 2,04 %**	**0,86 %**	**- 3,35 %**
2030	**"This model"**	431.283	344.212	355.084	358.554	370.113
	RB model	389.404	365.236	375.434	371.108	377.437
	Difference	41.879	- 21.024	- 20.350	- 12.554	- 7.324
		10,75 %	**- 5,76 %**	**- 5,42 %**	**- 3,38 %**	**- 1,94 %**

Table 4.11 shows the percentage variations of the results of the two models in order to compare the models and to establish when they work in the same way and when the outputs are quite different. As for truck tractor 4x2, Diesel powertrain always gives the worst results

because the differences are between 8% and 11%, so it is not possible to neglect these differences. For other alternative powertrains, the differences are very small and they are both positive and negative, that means that sometimes the TCO evaluated according to "This model" are higher than the TCO of RB model, whereas in other years it is the opposite. In particular, it is possible to see how the results for BET technology are always higher for Roland Berger model, with a difference of 2-3,5%. The best results in terms of equal results are related to FCET technologies, especially in the first period (2023 and 2027). According to the values in the table above, FCET at 350 and 700 bar, in 2023, present a very small differences (0,25% and 0,62%, respectively), so in this case the two models are interchangeable. For what concern 2027, the best results are given by FCET LH_2, with a positive percentage difference between the models equal to 0,86%. In 2030 all the alternative engines are underestimate, with BET trucks that give the best results (-1,94%).

4.2.1.3 Rigid 4x2

The last type of truck analysed is the rigid 4x2 used for the short-haul segment (around 60.000 km/year) and the results of the TCO estimation, for both models, are reported in Table 4.12:

Table 4.12 Comparison of the TCO of the models (rigid 4x2)

Comparison of the TCO of the models (rigid 4x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**"This model"**	279.196	301.797	310.634	315.823	283.512
	RB model	259.967	301.435	309.202	311.338	293.198
	Difference	19.229	362	1.432	4.485	- 9.686
		7,40 %	**0,12 %**	**0,46 %**	**1,44 %**	**- 3,30 %**
2027	**"This model"**	281.497	250.303	257.473	257.722	242.171
	RB model	260.155	257.061	263.399	262.095	252.454
	Difference	21.342	- 6.758	- 5.926	- 4.373	- 10.283
		8,20 %	**- 2,63 %**	**- 2,25 %**	**- 1,67 %**	**- 4,07 %**
2030	**"This model"**	282.604	227.936	234.187	231.958	225.132
	RB model	258.617	241.626	247.535	245.751	234.990
	Difference	23.987	- 13.690	- 13.348	- 13.793	- 9.858
		9,28 %	**- 5,67 %**	**- 5,39 %**	**- 5,61 %**	**- 4,20 %**

The values follow almost the same trends of the previous cases, particularly for Diesel trucks in which there is an increase of the difference over the years (from 7,40% in 2023 to 9,28% in 2030), but with values slightly lower with respect to the previous typologies. Concerning other technologies, in 2023 only BETs are underestimate from "This model" (-3,30%), whereas all FCET technologies are slightly overestimate (between 0,12% and 1,44%). In 2027 and 2030, all alternative powertrains present a TCO in RB model higher than "This model", even if the differences are very small (around -2% in 2027 and around -5,5% in 2030). Globally, the best estimation of "This model" comparing to RB model is for FCET at 350 bar in 2030, where the difference between the TCO is only 362 € (0,12%).

4.2.2 1st and 2nd life comparison in different years

The same analysis done in the above section is done here. 1st and 2nd life of a truck refers to a period of 10 years (for the assumptions and the considerations done in the previous chapters) in which the truck's components achieve the end of their life, so they need to be replaced.

The values to be compared are reported in the following tables and each of them is analysed to determine the comparability of the two models.

4.2.2.1 Tractor 4x2

This first technology is the most widespread in the transport sector, therefore its analysis must be done carefully. The values obtained from the models are reported in Table 4.13:

Table 4.13 Comparison of the TCO of the models (tractor 4x2)

Comparison of the TCO of the models (tractor 4x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**"This model"**	1.307.475	1.501.378	1.558.717	1.571.353	1.831.858
	RB model	1.116.161	1.319.523	1.362.144	1.344.253	1.515.633
	Difference	191.314	181.855	196.573	227.100	316.225
		17,14 %	**13,78 %**	**14,43 %**	**16,89 %**	**20,86 %**
2027	**"This model"**	1.327.593	1.175.172	1.221.326	1.208.210	1.442.782
	RB model	1.107.067	1.108.184	1.144.192	1.121.571	1.264.458
	Difference	220.526	66.988	77.134	86.639	178.324
		19,92 %	**6,04%**	**6,74%**	**7,72 %**	**14,10 %**
2030	**"This model"**	1.339.537	1.035.303	1.076.168	1.048.500	1.326.660
	RB model	1.098.292	1.031.356	1.065.640	1.045.897	1.172.828
	Difference	241.245	3.947	10.528	2.603	153.832
		21,97 %	**0,38 %**	**0,99 %**	**0,25 %**	**13,12 %**

Although the values are different from the analysis of the 1st life only (in this case they are almost twice), the trends and then the considerations are very similar. Diesel trucks variations are generally bigger than the variations of the other technologies, but in 2023 the worst result is related to BET: it has a difference in the results from the two models equal to 316.225 €/truck corresponding to 20,86% ("This model" overestimates the TCO). In 2030 the two models achieve very similar results for FCET technologies: for FCET at 350 bar the percentage difference is 0,38%, for FCET at 700 bar is 0,99%, and for FCET LH_2 the variation is equal to 1,25%. In conclusion, it is possible to say that, except for conventional technology, for all the other trucks the two models have similar results.

4.2.2.2 Rigid 6x2

Table 4.14 summarises the TCO obtained from the two models with the same assumptions in three different years, as for the previous analyses:

Table 4.14 Comparison of the TCO of the models (rigid 6x2)

Comparison of the TCO of the models (rigid 6x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**“This model”**	791.300	888.682	919.390	932.354	945.230
	RB model	730.960	838.238	863.235	858.089	878.342
	Difference	60.340	50.444	56.155	74.265	66.888
		8,25 %	**6,02 %**	**6,51 %**	**8,65 %**	**7,62 %**
2027	**“This model”**	799.890	707.414	732.209	729.540	765.937
	RB model	725.745	715.505	736.831	727.411	756.135
	Difference	74.145	- 8.091	- 4.622	2.129	9.802
		10,22 %	**- 1,13 %**	**- 0,63 %**	**0,29 %**	**1,30 %**
2030	**“This model”**	804.364	630.222	651.966	641.084	704.209
	RB model	720.709	672.372	692.767	684.116	701.818
	Difference	83.655	- 42.150	- 40.801	- 43.032	2.391
		11,61 %	**- 6,27 %**	**- 5,89 %**	**- 6,29 %**	**0,34 %**

The most important difference is related to BET technology: if for tractor 4x2 BET is almost always the worst technology in terms of difference between the models, in this case is one of the best alternatives. In 2023 only FCET at 350 and 700 bar are better, whereas in 2030 it is the best one with a percentage difference of 0,34% (corresponding to only 2.391 €/truck), so RB model underestimates the TCO with respect to “This model”. The best result is obtained evaluating the TCO of FCET LH_2 in 2027: the difference is only 2.129 €/truck (0,29%).

4.2.2.3 Rigid 4x2

The last comparison of the two models is related to the short-haul segment trucks. The outputs of the models are shown in Table 4.15:

Table 4.15 Comparison of the TCO of the models (rigid 4x2)

Comparison of the TCO of the models (rigid 4x2) [€/truck]						
		Diesel truck	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	**“This model”**	503.692	548.893	566.566	576.945	531.832
	RB model	468.349	520.165	534.482	534.062	511.855
	Difference	35.343	28.728	32.084	42.883	19.977
		7,55 %	**5,52 %**	**6,00 %**	**8,03 %**	**3,90 %**
2027	**“This model”**	508.293	445.904	460.244	460.742	443.300
	RB model	465.791	452.839	465.209	461.611	444.982
	Difference	42.502	- 6.935	- 4.965	- 869	- 1.682
		9,12 %	**- 1,53 %**	**- 1,07 %**	**- 0,19 %**	**- 0,38 %**
2030	**“This model”**	510.507	401.171	413.673	409.214	408.580
	RB model	462.633	428.652	440.470	436.903	415.379
	Difference	47.874	- 27.481	- 26.797	- 27.689	- 6.799
		10,35 %	**- 6,41 %**	**- 6,08 %**	**- 6,34 %**	**- 1,64 %**

In this analysis the trend is similar to the previous one: Diesel trucks have always the highest variations (7-11% more for “This model” compared to RB model), BET is one of the best technologies regarding the differences between the models and in 2027 are obtained the best results. Particularly, the smallest variations are obtained in 2027 for FCET LH_2 and BET with a difference in the TCO of 869 €/truck for FCET and 1.682 €/truck for BET (-0,19% and -0,38% respectively).

4.3 Final considerations

Summarising the results obtained for 1st and 2nd life combined, the most important points to highlight are the following:

- TCO of Diesel trucks is always overestimated by “This model” compared to RB model and this overestimation decreases by decreasing the annual mileage, whereas increases over the years. It follows that the worst match between the results of the two models is for 4x2 Diesel tractor in 2030, with a difference of 241.245 €/truck (21,97 %);
- The best correspondence between the models is obtained in 2027 for FCET LH_2 rigid 4x2, with a very small variation between the two outputs: only 869 €/truck of difference, corresponding to 0,19%;
- In general, FCETs give the best matches between the two models, especially in 2027 where the values of the differences are between 0,29% and 1,13% (in absolute value), but in any case, even in the other years the variation in the results is never higher than 10% (except for 2023).

5. Sensitivity analysis

In the previous chapters the results obtained on the basis of certain assumptions and considerations have been examined and analysed, therefore the results are in function of these assumptions. It is useful to understand which parameters most affect the TCO, so a sensitivity analysis is the best way to understand it. The objective of this analysis is to determine which input parameters are necessary to modify in order to achieve the goal of a TCO of alternative powertrains lower than the TCO of conventional trucks as soon as possible for all the three truck typologies.

The parameters chosen for this analysis are:

- Country
- Motor vehicle tax and registration fee
- Road toll
- Energy/Fuel price
- Homogeneity of the driving profile
- Market maturity
- Annual mileage

In the following sections each parameter is analysed separately.

5.1 Country

The model gives the possibility to choose between different countries and for each country some parameters change, such as motor vehicle tax, registration fee, road toll, Diesel price, and share of empty runs factor. It is useful to compare the results for each country in order to understand in which of them it is more convenient to do these investments.

The possible countries from which it is possible to choose among are Albania, Croatia, Czechia, France, Germany, Greece, Hungary, Ireland, Italy, Norway, Poland, Portugal, Slovakia, Spain, and United Kingdom. Consequently, the model changes the parameters above mentioned and it is possible to analyse the results in terms of TCO.

The analysis is divided for each truck types in order to do not have a single table with too many results that is not easy to read it. Therefore, each typology (tractor 4x2, rigid 6x2, and rigid 4x2) is analysed separately.

Then, a ranking of the best and worst countries it will be done for each truck typology.

5.1.1 Tractor 4x2

In the following tables all the results for 2023, 2027, and 2030 are reported for each country considering 1st and 2nd life combined:

Table 5.1 TCO for each country in 2023 (tractor 4x2)

TCO for each country in 2023 (tractor 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Albania	1.153.022	1.440.473	1.497.812	1.510.448	1.770.954
Croatia	**1.100.633**	1.391.193	1.443.923	1.455.543	1.679.326
Czechia	1.319.720	1.682.965	1.742.279	1.755.351	2.031.594
France	1.342.450	1.522.087	1.580.743	1.593.669	1.864.666
Germany	1.351.256	1.591.432	1.646.796	1.658.997	1.903.764
Greece	1.126.786	**1.363.364**	**1.413.460**	**1.424.500**	**1.627.300**
Hungary	1.252.597	1.568.837	1.624.201	1.636.401	1.881.169
Ireland	1.207.499	1.461.605	1.509.726	1.520.330	1.707.392
Italy	1.307.475	1.501.378	1.558.717	1.571.353	1.831.858
Norway	1.180.056	1.453.761	1.505.174	1.516.504	1.729.796
Poland	1.186.290	1.535.808	1.591.171	1.603.372	1.848.140
Portugal	1.139.014	1.473.639	1.530.319	1.542.810	1.798.069
Slovakia	1.312.900	1.633.894	1.689.257	1.701.458	1.946.226
Spain	1.175.007	1.473.539	1.527.586	1.539.497	1.773.772
United Kingdom	**1.562.231**	**1.706.781**	**1.764.120**	**1.776.756**	**2.037.261**

In 2023 the best country for almost all technologies is Greece, only for Diesel truck the best one is Croatia. Other countries with good values are Albania, Portugal, Norway, and Ireland. The worst country is the United Kingdom, followed by Germany, Czechia, and Slovakia. These results are mainly influenced by two parameters: road toll (for all technologies) and Diesel price (only for Diesel trucks). In terms of road toll, the worst countries are United Kingdom (0,23 €/km), Czechia (0,19 €/km), and Slovakia (0,19 €/km), whereas the best are Albania (0,04 €/km) and Croatia (0,06 €/km). Regarding Diesel price, the best countries are Czechia (1,51 €/l), Poland (1,51 €/l), and Portugal (1,55 €/l), whereas the worst are United Kingdom (1,94 €/l) and France (1,87 €/l).

In 2027 the situation is the one summarised in Table 5.2:

Table 5.2 TCO for each country in 2027 (tractor 4x2)

TCO for each country in 2027 (tractor 4x2)					
	Diesel	FCET 350 bar	FCET 700 bar	FCET LH_2	BET
Albania	1.175.268	1.114.268	1.160.422	1.147.305	1.381.878
Croatia	**1.120.048**	1.082.329	1.124.687	1.112.650	1.319.471
Czechia	1.344.891	1.349.327	1.397.108	1.383.529	1.629.995
France	1.363.136	1.190.926	1.238.164	1.224.740	1.467.241
Germany	1.371.137	1.272.659	1.317.186	1.304.532	1.527.211
Greece	1.143.161	**1.064.411**	**1.104.599**	**1.093.178**	**1.284.142**
Hungary	1.274.270	1.250.064	1.294.591	1.281.937	1.504.616
Ireland	1.223.077	1.170.084	1.208.645	1.197.687	1.376.758
Italy	1.327.593	1.175.172	1.221.326	1.208.210	1.442.782
Norway	1.198.231	1.149.853	1.191.126	1.179.397	1.378.290
Poland	1.208.747	1.217.034	1.261.561	1.248.907	1.471.587
Portugal	1.161.927	1.149.910	1.195.522	1.182.560	1.413.168
Slovakia	1.334.685	1.315.120	1.359.647	1.346.993	1.569.673
Spain	1.195.439	1.159.721	1.203.163	1.190.818	1.405.568
United Kingdom	**1.581.229**	**1.380.575**	**1.426.729**	**1.413.612**	**1.648.185**

As before, the best country for alternative trucks is Greece, whereas the worst one is United Kingdom. The differences between these two countries is between 316.164 € and 364.043 € for FCETs and BET technologies, whereas is of 461.181€ for Diesel trucks.

The last year considered is 2030, in which the outputs of the model are reported in Table 5.3:

Table 5.3 TCO for each country in 2030 (tractor 4x2)

TCO for each country in 2030 (tractor 4x2)					
	Diesel	FCET 350 bar	FCET 700 bar	FCET LH_2	BET
Albania	1.188.808	974.398	1.015.264	987.596	1.265.755
Croatia	**1.131.465**	952.295	989.740	964.388	1.211.466
Czechia	1.360.624	1.205.242	1.247.574	1.218.913	1.510.394
France	1.375.506	1.048.246	1.090.090	1.061.760	1.348.800
Germany	1.382.903	1.137.005	1.176.404	1.149.729	1.414.568
Greece	1.152.297	**939.997**	**975.487**	**951.458**	**1.180.775**
Hungary	1.287.380	1.114.409	1.153.809	1.127.134	1.391.972
Ireland	1.231.615	1.049.885	1.083.909	1.060.873	1.276.869
Italy	1.339.537	1.035.303	1.076.168	1.048.500	1.326.660
Norway	1.208.718	1.022.629	1.059.096	1.034.406	1.272.603
Poland	1.222.445	1.081.380	1.120.780	1.094.104	1.358.943
Portugal	1.175.967	1.011.446	1.051.823	1.024.486	1.298.205
Slovakia	1.347.879	1.179.466	1.218.866	1.192.190	1.457.029
Spain	1.207.618	1.026.877	1.065.299	1.039.285	1.295.243
United Kingdom	**1.592.332**	**1.240.705**	**1.281.571**	**1.253.903**	**1.532.063**

Even in this case it is possible to do the same considerations as before: Greece is the best country, whereas United Kingdom is the worst one.

5.1.2 Rigid 6x2

In the following tables are reported the results for each country for 2023, 2027, and 2030 considering truck rigid 6x2 (1st and 2nd life combined is considered):

Table 5.4 TCO for each country in 2023 (rigid 6x2)

TCO for each country in 2023 (rigid 6x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH₂**	**BET**
Albania	696.412	845.777	876.486	889.450	902.325
Croatia	**670.808**	823.147	851.395	863.320	865.825
Czechia	814.544	1.005.490	1.037.253	1.050.662	1.067.983
France	810.102	899.205	930.616	943.877	959.716
Germany	829.889	953.515	983.169	995.688	1.004.119
Greece	688.149	**811.189**	**838.032**	**849.363**	**845.943**
Hungary	774.021	939.919	969.574	982.092	990.524
Ireland	750.890	884.209	909.997	920.883	913.018
Italy	791.300	888.682	919.390	932.354	945.230
Norway	725.699	868.901	896.446	908.075	907.617
Poland	731.497	915.890	945.544	958.063	966.494
Portugal	694.777	870.535	900.892	913.708	925.102
Slovakia	818.436	986.976	1.016.630	1.029.149	1.037.580
Spain	720.894	877.307	906.259	918.481	923.949
United Kingdom	**956.680**	**1.026.585**	**1.057.293**	**1.070.257**	**1.083.133**

In 2023 the best country for almost all technologies is again Greece, only for Diesel truck the best country is Croatia. Albania, Croatia, Greece, and Portugal are the only countries with a TCO lower than 700.000 €/truck for Diesel trucks. Other countries with a good TCO are Portugal, Albania, and Norway. As before, United Kingdom is the worst country (the only one with a TCO higher than 900.000 €/truck for conventional trucks). For all alternative powertrains the TCO is higher than 1.000.000 €/truck and only another country has the same results: Czechia. Other countries with bad results are Slovakia, Germany, Ireland, and Hungary.

The situation in 2027 is the reported in Table 5.5:

Table 5.5 TCO for each country in 2027 (rigid 6x2)

TCO for each country in 2027 (rigid 6x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH₂**	**BET**
Albania	706.445	664.510	689.304	686.636	723.032
Croatia	**679.316**	651.112	673.864	671.415	699.724
Czechia	826.393	820.266	845.936	843.174	883.036
France	818.964	715.299	740.678	737.947	776.653
Germany	838.487	776.204	800.123	797.549	830.479
Greece	694.818	**644.431**	**666.015**	**663.692**	**687.380**
Hungary	783.835	762.609	786.528	783.954	816.884
Ireland	757.188	721.407	742.116	739.887	760.109
Italy	799.890	707.414	732.209	729.540	765.937
Norway	733.478	699.504	721.672	719.286	745.285
Poland	741.843	738.580	762.499	759.925	792.855
Portugal	705.320	690.587	715.090	712.453	747.694
Slovakia	828.326	809.666	833.585	831.011	863.941
Spain	729.979	702.635	725.970	723.459	754.079
United Kingdom	**964.510**	**845.317**	**870.112**	**867.443**	**903.839**

The best country is always Greece and the worst one is always United Kingdom. There are other countries with bad values in terms of TCO: these countries are Germany (regarding Diesel trucks' TCO) and Czechia (regarding the TCO of alternative trucks). After Greece and Croatia, the best countries are Portugal and Norway.

In 2030, the last year considered for the analysis, the outputs of the model are reported in Table 5.6:

Table 5.6 TCO for each country in 2030 (rigid 6x2)

TCO for each country in 2030 (rigid 6x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Albania	712.003	587.318	609.062	598.180	661.305
Croatia	**683.729**	579.260	599.173	589.207	642.271
Czechia	833.313	740.786	763.314	752.040	819.477
France	823.643	636.582	658.849	647.705	713.705
Germany	842.968	701.301	722.260	711.771	770.584
Greece	697.853	**575.630**	**594.497**	**585.055**	**632.369**
Hungary	789.228	687.706	708.665	698.176	756.989
Ireland	759.945	654.895	672.977	663.928	706.930
Italy	804.364	630.222	651.966	641.084	704.209
Norway	737.344	629.178	648.568	638.864	689.053
Poland	747.635	663.676	684.636	674.146	732.959
Portugal	711.260	614.158	635.640	624.889	686.577
Slovakia	833.776	734.762	755.722	745.232	804.045
Spain	734.825	629.257	649.693	639.466	695.405
United Kingdom	**968.414**	**768.125**	**789.869**	**778.987**	**842.112**

In 2030 the situation is the same as 2023, with United Kingdom like the worst country and Greece and Croatia as best ones. The difference between the TCO of these countries for alternative trucks is around 198.000 €/truck, whereas for Diesel vehicles is 284.685 €/truck. Croatia, Norway, and Portugal follow Greece in the ranking of the best countries, whereas Czechia and Slovakia are immediately behind United Kingdom in this special ranking.

5.1.3 Rigid 4x2

Table 5.7 shows the TCO in 2023 for each country considering truck rigid 4x2:

Table 5.7 TCO for each country in 2023 (rigid 4x2)

TCO for each country in 2023 (rigid 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Albania	443.893	519.988	537.662	548.041	502.927
Croatia	429.669	508.197	524.476	534.037	487.327
Czechia	519.044	619.556	637.827	648.557	604.128
France	514.213	554.319	572.391	583.004	538.346
Germany	528.798	589.871	606.947	616.976	571.178
Greece	441.472	502.933	518.416	527.509	479.888
Hungary	497.067	583.276	600.352	610.380	564.583
Ireland	484.233	552.098	566.983	575.725	527.420
Italy	503.692	548.893	566.566	576.945	531.832
Norway	464.881	538.048	553.929	563.256	516.090
Poland	469.040	566.246	583.322	593.351	547.554
Portugal	444.917	536.795	554.269	564.532	519.190
Slovakia	528.552	616.332	633.408	643.437	597.640
Spain	462.500	543.261	559.938	569.733	523.480
United Kingdom	605.471	634.295	651.969	662.348	617.235

The best and worst countries are Greece (Croatia for Diesel trucks) and United Kingdom, respectively. Albania, Croatia, Norway, and Portugal have similar results as Greece, but slightly higher, whereas other bad countries in term of results are Czechia, Germany, and Slovakia.

In 2027 the situation and the results of the TCO analysis are the one reported in Table 5.8:

Table 5.8 TCO for each country in 2027 (rigid 4x2)

TCO for each country in 2027 (rigid 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Albania	449.407	417.000	431.340	431.838	414.395
Croatia	434.301	410.429	423.603	424.061	405.155
Czechia	525.670	514.330	529.170	529.685	512.870
France	518.964	449.839	464.512	465.022	447.997
Germany	533.440	489.120	502.961	503.441	485.372
Greece	444.989	408.149	420.657	421.092	401.349
Hungary	502.477	482.525	496.365	496.846	478.776
Ireland	487.550	459.551	471.560	471.977	451.608
Italy	508.293	445.904	460.244	460.742	443.300
Norway	469.075	441.772	454.613	455.059	435.735
Poland	474.786	465.496	479.336	479.817	461.747
Portugal	450.764	434.552	448.726	449.218	431.567
Slovakia	534.010	515.582	529.422	529.903	511.833
Spain	467.473	444.001	457.509	457.978	439.490
United Kingdom	609.593	531.307	545.647	546.145	528.703

Greece and United Kingdom are confirmed as best and worst countries respectively, as for all the previous cases. The same considerations done for the previous analysis (2023) can be done for 2027.

The last analysis is done for 2030, in which the TCO obtained from the model are summarised in Table 5.9:

Table 5.9 TCO for each country in 2030 (rigid 4x2)

TCO for each country in 2030 (rigid 4x2)					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
Albania	452.305	372.267	384.768	380.309	379.676
Croatia	**436.537**	368.763	380.225	376.137	372.830
Czechia	529.401	468.282	481.230	476.612	477.124
France	521.290	404.229	417.028	412.463	412.593
Germany	535.685	445.701	457.757	453.457	451.678
Greece	446.390	**368.235**	**379.103**	**375.227**	**370.393**
Hungary	505.297	439.106	451.162	446.862	445.083
Ireland	488.801	420.952	431.374	427.657	421.677
Italy	510.507	401.171	413.673	409.214	408.580
Norway	470.984	400.982	412.147	408.165	404.094
Poland	477.858	422.077	434.133	429.833	428.054
Portugal	453.912	390.257	402.610	398.204	397.189
Slovakia	536.866	472.163	484.219	479.919	478.140
Spain	469.965	401.459	413.218	409.024	406.481
United Kingdom	**611.447**	**486.574**	**499.075**	**494.617**	**493.983**

United Kingdom is the only country with a TCO higher than 600.000 €/truck for Diesel trucks and higher than 485.000 €/truck for all alternative trucks. Other countries with similar results, particularly for alternative trucks, are Slovakia and Czechia. On the other hand, the best country is always Greece (except for conventional trucks that is again Croatia), followed by Albania, Croatia, and Portugal.

5.2 Motor vehicle tax and registration fee

This sensitivity analysis is carried out only for one country because the goal is only to study how the variation of these parameters affects the results, so it is irrelevant the country studied. Then, the country chosen is Italy and this choice is the same for the parameters that will be subsequently analysed.

As it is possible to see for example from Table 3.1 and from Figure 3.1, motor vehicle tax and registration fee account together for less than 2%, so they do not affect the TCO in a significant way.

In the Table 5.10, Table 5.11, and Table 5.12 it is possible to see how the TCO changes by changing these two parameters:

Table 5.10 Motor vehicle tax and registration fee variations analysis (tractor 4x2)

Motor vehicle tax and registration fee variations analysis – Percentage variations of TCO (tractor 4x2)									
		2023	2024	2025	2026	2027	2028	2029	2030
Diesel	**± 50 %**	±0,25%	±0,25%	±0,25%	±0,25%	±0,25%	±0,25%	±0,25%	±0,25%
FCET 350 bar	**± 50 %**	±0,22%	±0,23%	±0,24%	±0,25%	±0,28%	±0,30%	±0,31%	±0,32%
FCET 700 bar	**± 50 %**	±0,21%	±0,22%	±0,23%	±0,24%	±0,27%	±0,28%	±0,30%	±0,31%
FCET LH_2	**± 50 %**	±0,21%	±0,22%	±0,23%	±0,25%	±0,28%	±0,29%	±0,30%	±0,32%
BET	**± 50 %**	±0,18%	±0,19%	±0,19%	±0,19%	±0,23%	±0,24%	±0,24%	±0,25%

Table 5.11 Motor vehicle tax and registration fee variations analysis (rigid 6x2)

Motor vehicle tax and registration fee variations analysis – Percentage variations of TCO (rigid 6x2)									
		2023	2024	2025	2026	2027	2028	2029	2030
Diesel	**± 50 %**	±0,42%	±0,42%	±0,42%	±0,42%	±0,42%	±0,41%	±0,41%	±0,41%
FCET 350 bar	**± 50 %**	±0,37%	±0,39%	±0,41%	±0,42%	±0,47%	±0,49%	±0,51%	±0,53%
FCET 700 bar	**± 50 %**	±0,36%	±0,38%	±0,39%	±0,41%	±0,45%	±0,47%	±0,49%	±0,51%
FCET LH_2	**± 50 %**	±0,36%	±0,37%	±0,39%	±0,41%	±0,46%	±0,48%	±0,50%	±0,52%
BET	**± 50 %**	±0,35%	±0,36%	±0,37%	±0,38%	±0,43%	±0,44%	±0,46%	±0,47%

Table 5.12 Motor vehicle tax and registration fee variations analysis (rigid 4x2)

Motor vehicle tax and registration fee variations analysis – Percentage variations of TCO (rigid 4x2)									
		2023	2024	2025	2026	2027	2028	2029	2030
Diesel	**± 50 %**	±0,66%	±0,66%	±0,66%	±0,66%	±0,65%	±0,65%	±0,65%	±0,65%
FCET 350 bar	**± 50 %**	±0,61%	±0,63%	±0,66%	±0,68%	±0,75%	±0,77%	±0,80%	±0,83%
FCET 700 bar	**± 50 %**	±0,59%	±0,61%	±0,64%	±0,66%	±0,72%	±0,75%	±0,78%	±0,80%
FCET LH_2	**± 50 %**	±0,58%	±0,60%	±0,63%	±0,66%	±0,72%	±0,75%	±0,78%	±0,81%
BET	**± 50 %**	±0,63%	±0,64%	±0,66%	±0,67%	±0,75%	±0,77%	±0,80%	±0,81%

For this analysis a variation of ±50% is considered. The results show how the TCO variations are negligible with respect to the TCO (always lower than 1%) and considering that both parameters are fixed and they do not depend on other parameters, such as annual mileage, the variations are more significant for short-haul segment (rigid 4x2) because the TCO are lower.

5.3 Road toll

Road toll is the parameter that mostly affects the final results of the model because it depends on the annual mileage.

The sensitivity analysis considers first a variation of ±50% with respect to the standard value (considering Italy as country), then another situation is considered, that is the situation in which the road toll for zero-emission trucks is free, whereas for Diesel trucks is equals to the standard value. This last case is a possible actual case in which Governments decide to introduce subsidies of zero-emission vehicles at the expense of conventional powertrains in order to promote the transition toward carbon neutrality as establish from the European Union.

Even in this case, the analysis is divided for each truck typology and for the first case the results are summarised in the following tables:

Table 5.13 Road toll variations analysis – case 1 (tractor 4x2)

Road toll variations analysis – Percentage variations of TCO (tractor 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50 %**	±4,28%	±4,27%	±4,25%	±4,23%	±4,22%	±4,21%	±4,19%	±4,18%
FCET 350 bar	**± 50 %**	±3,73%	±3,91%	±4,09%	±4,27%	±4,77%	±4,97%	±5,19%	±5,41%
FCET 700 bar	**± 50 %**	±3,59%	±3,76%	±3,94%	±4,11%	±4,59%	±4,79%	±4,99%	±5,20%
FCET LH_2	**± 50 %**	±3,56%	±3,75%	±3,95%	±4,15%	±4,63%	±4,86%	±5,10%	±5,34%
BET	**± 50 %**	±3,06%	±3,12%	±3,22%	±3,28%	±3,88%	±3,97%	±4,12%	±4,22%

Table 5.14 Road toll variations analysis – case 1 (rigid 6x2)

Road toll variations analysis – Percentage variations of TCO (rigid 6x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50 %**	±4,80%	±4,79%	±4,77%	±4,76%	±4,75%	±4,74%	±4,73%	±4,72%
FCET 350 bar	**± 50 %**	±4,28%	±4,46%	±4,65%	±4,85%	±5,37%	±5,59%	±5,81%	±6,03%
FCET 700 bar	**± 50 %**	±4,13%	±4,32%	±4,50%	±4,69%	±5,19%	±5,40%	±5,61%	±5,83%
FCET LH_2	**± 50 %**	±4,08%	±4,28%	±4,48%	±4,70%	±5,21%	±5,44%	±5,69%	±5,93%
BET	**± 50 %**	±4,02%	±4,10%	±4,24%	±4,33%	±4,96%	±5,08%	±5,27%	±5,40%

Table 5.15 Road toll variations analysis – case 1 (rigid 4x2)

Road toll variations analysis – Percentage variations of TCO (rigid 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50 %**	±4,76%	±4,76%	±4,74%	±4,73%	±4,72%	±4,71%	±4,71%	±4,70%
FCET 350 bar	**± 50 %**	±4,37%	±4,55%	±4,73%	±4,91%	±5,38%	±5,58%	±5,78%	±5,98%
FCET 700 bar	**± 50 %**	±4,24%	±4,41%	±4,59%	±4,76%	±5,21%	±5,41%	±5,60%	±5,80%
FCET LH_2	**± 50 %**	±4,16%	±4,35%	±4,55%	±4,75%	±5,21%	±5,42%	±5,65%	±5,86%
BET	**± 50 %**	±4,51%	±4,60%	±4,76%	±4,85%	±5,41%	±5,53%	±5,74%	±5,87%

All the tables above show how the TCO changes as a function of the road toll for each typology of truck and it is possible to see that the percentage variations are between ±3% and ±6% with an increase over years for alternative technologies (FCETs and BET), whereas for Diesel trucks in 2023 the variation is more significant (although the decrease is very low).

The second scenario (case 2) is the one described above in which only alternative powertrains are free from road toll, whereas Diesel trucks are subject to a full road toll:

Table 5.16 Road toll variations analysis – case 2 (tractor 4x2)

Road toll variations analysis – Percentage variations of TCO (tractor 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	-7,46%	-7,81%	-8,17%	-8,54%	-9,53%	-9,95%	-10,39%	-10,82%
FCET 700 bar	-7,19%	-7,53%	-7,88%	-8,23%	-9,17%	-9,58%	-9,98%	-10,41%
FCET LH_2	-7,13%	-7,51%	-7,90%	-8,30%	-9,27%	-9,72%	-10,21%	-10,68%
BET	-6,11%	-6,24%	-6,44%	-6,56%	-7,76%	-7,95%	-8,24%	-8,44%

Table 5.17 Road toll variations analysis – case2 (rigid 6x2)

Road toll variations analysis – Percentage variations of TCO (rigid 6x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	-8,55%	-8,93%	-9,31%	-9,70%	-10,74%	-11,17%	-11,62%	-12,06%
FCET 700 bar	-8,27%	-8,63%	-9,01%	-9,38%	-10,38%	-10,80%	-11,22%	-11,66%
FCET LH_2	-8,15%	-8,55%	-8,97%	-9,39%	-10,42%	-10,88%	-11,38%	-11,85%
BET	-8,04%	-8,20%	-8,48%	-8,65%	-9,92%	-10,15%	-10,54%	-10,79%

Table 5.18 Road toll variations analysis – case 2 (rigid 4x2)

Road toll variations analysis – Percentage variations of TCO (rigid 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	-8,74%	-9,10%	-9,46%	-9,82%	-10,76%	-11,16%	-11,57%	-11,96%
FCET 700 bar	-8,47%	-8,82%	-9,18%	-9,53%	-10,43%	-10,82%	-11,21%	-11,60%
FCET LH$_2$	-8,32%	-8,70%	-9,10%	-9,49%	-10,42%	-10,85%	-11,30%	-11,73%
BET	-9,03%	-9,21%	-9,52%	-9,71%	-10,83%	-11,07%	-11,48%	-11,75%

In this case the reductions are important because the trucks free from road toll are subject to a percentage reduction between 6,11% (for BET tractor 4x2 in 2023) and 12,06% (for rigid 6x2 FCET at 350 bar in 2030).

For tractor 4x2 BETs have the lowest reductions. FCETs have almost the same trend for all typologies, even if for tractor 4x2 the values are slightly lower than for the other two typologies.

5.4 Energy/Fuel price

Energy price is composed by three parts: the cost without taxation and surcharges, the taxation, and the surcharges. The sensitivity analysis is done by changing the taxation applied to the fuel, considering ±50% of the taxation and the surcharges and analysing the variations of the TCO. The following tables summarised the results for each truck type:

Table 5.19 Energy/Fuel price variations analysis (tractor 4x2)

Energy/Fuel price variations analysis – Percentage variations of TCO (tractor 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50%**	±18,08%	±18,28%	±18,45%	±18,65%	±18,85%	±19,04%	±19,23%	±19,41%
FCET 350 bar	**± 50%**	±16,12%	±15,62%	±15,12%	±14,60%	±15,08%	±14,53%	±13,99%	±13,46%
FCET 700 bar	**± 50%**	±17,18%	±16,69%	±16,19%	±15,70%	±16,26%	±15,71%	±15,22%	±14,68%
FCET LH$_2$	**± 50%**	±18,68%	±18,06%	±17,41%	±16,74%	±17,12%	±16,44%	±15,73%	±15,07%
BET	**± 50%**	±14,66%	±14,27%	±13,43%	±12,99%	±14,55%	±14,07%	±12,98%	±12,44%

Table 5.20 Energy/Fuel price variations analysis (rigid 6x2)

Energy/Fuel price variations analysis – Percentage variations of TCO (rigid 6x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50 %**	±16,60%	±16,78%	±16,94%	±17,12%	±17,29%	±17,46%	±17,63%	±17,80%
FCET 350 bar	**± 50 %**	±15,00%	±14,47%	±13,95%	±13,41%	±13,73%	±13,17%	±12,61%	±12,07%
FCET 700 bar	**± 50 %**	±16,04%	±15,52%	±15,00%	±14,48%	±14,87%	±14,29%	±13,78%	±13,23%
FCET LH$_2$	**± 50 %**	±17,35%	±16,69%	±16,01%	±15,31%	±15,54%	±14,84%	±14,13%	±13,45%
BET	**± 50 %**	±15,65%	±15,23%	±14,33%	±13,85%	±15,02%	±14,50%	±13,37%	±12,79%

Table 5.21 Energy/Fuel price variations analysis (rigid 4x2)

Energy/Fuel price variations analysis – Percentage variations of TCO (rigid 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**± 50 %**	±15,50%	±15,67%	±15,81%	±15,98%	±16,14%	±16,30%	±16,46%	±16,61%
FCET 350 bar	**± 50 %**	±14,30%	±13,75%	±13,21%	±12,65%	±12,80%	±12,23%	±11,66%	±11,13%
FCET 700 bar	**± 50 %**	±15,33%	±14,78%	±14,23%	±13,69%	±13,90%	±13,31%	±12,79%	±12,23%
FCET LH$_2$	**± 50 %**	±16,50%	±15,82%	±15,12%	±14,41%	±14,46%	±13,75%	±13,04%	±12,37%
BET	**± 50 %**	±16,38%	±15,92%	±14,98%	±14,47%	±15,25%	±14,70%	±13,54%	±12,94%

The variation in the energy/fuel cost leads to a high TCO variation thanks to its relationship with the annual mileage. These variations are higher in 2023 than in other years, whereas in 2030 they reach their minimum values. The costs of energy of BETs are mostly change for short-haul segment than for long-haul segment: for tractor 4x2 the variation is between ±12,44% (2030) and ±14,66% (2023), for rigid 6x2 it is between ±12,79% (2030) and ±15,65% (2023), and for rigid 4x2 it is comprises between ±12,94% (2030) and ±16,38% (2023). Among the FCETs, the mostly influenced by this parameter is the FCET LH_2 with a variation between ±12,37% (rigid 4x2, in 2030) and ±18,68% (tractor 4x2, in 2023).

5.5 Homogeneity of the driving profile

This parameter affects the size of the hydrogen tank and the size of the batteries and it can be set choosing between four options: homogeneous (1,10), rather homogeneous (1,25), rather heterogeneous (1,50), and heterogeneous (1,75). As a standard value it is assumed that the driving profile is rather homogeneous, so this parameter is equal to 1,25.

In the following tables it is analysed how the TCO changes by changing this value, considering the percentage variations with respect to the TCO calculated with a coefficient equal to 1,25. Each typology is reported in a separate table:

Table 5.22 Driving profile coefficient variations analysis (tractor 4x2)

Driving profile coefficient variations analysis – Percentage variations of TCO (tractor 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**1,10**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,50	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,75	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**1,10**	-0,56%	-0,56%	-0,56%	-0,56%	-0,46%	-0,46%	-0,46%	-0,46%
	1,50	0,93%	0,93%	0,93%	0,93%	0,77%	0,77%	0,77%	0,76%
	1,75	1,85%	1,86%	1,86%	1,86%	1,53%	1,53%	1,53%	1,53%
FCET 700 bar	**1,10**	-0,58%	-0,58%	-0,58%	-0,59%	-0,47%	-0,48%	-0,48%	-0,48%
	1,50	0,97%	0,97%	0,97%	0,98%	0,79%	0,80%	0,80%	0,80%
	1,75	1,93%	1,94%	1,95%	1,95%	1,58%	1,59%	1,60%	1,61%
FCET LH_2	**1,10**	-0,28%	-0,27%	-0,27%	-0,27%	-0,19%	-0,18%	-0,18%	-0,18%
	1,50	0,46%	0,46%	0,45%	0,44%	0,31%	0,31%	0,30%	0,30%
	1,75	0,92%	0,91%	0,90%	0,89%	0,62%	0,61%	0,60%	0,59%
BET	**1,10**	-5,52%	-5,56%	-5,66%	-5,71%	-4,94%	-4,98%	-5,10%	-5,15%
	1,50	9,20%	9,26%	9,44%	9,52%	8,23%	8,29%	8,51%	8,58%
	1,75	18,39%	18,52%	18,87%	19,05%	16,46%	16,58%	17,02%	17,15%

Table 5.23 Driving profile coefficient variations analysis (rigid 6x2)

Driving profile coefficient variations analysis – Percentage variations of TCO (rigid 6x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**1,10**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,50	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,75	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**1,10**	-0,37%	-0,37%	-0,37%	-0,37%	-0,30%	-0,30%	-0,30%	-0,30%
	1,50	0,62%	0,62%	0,62%	0,62%	0,50%	0,50%	0,50%	0,49%
	1,75	1,24%	1,24%	1,24%	1,23%	1,01%	1,00%	0,99%	0,99%
FCET 700 bar	**1,10**	-0,39%	-0,39%	-0,39%	-0,39%	-0,31%	-0,31%	-0,31%	-0,31%
	1,50	0,65%	0,65%	0,65%	0,65%	0,52%	0,52%	0,52%	0,52%
	1,75	1,30%	1,30%	1,30%	1,30%	1,04%	1,04%	1,04%	1,04%
FCET LH$_2$	**1,10**	-0,19%	-0,18%	-0,18%	-0,18%	-0,12%	-0,12%	-0,12%	-0,11%
	1,50	0,31%	0,30%	0,30%	0,29%	0,20%	0,20%	0,19%	0,19%
	1,75	0,62%	0,61%	0,60%	0,59%	0,41%	0,40%	0,39%	0,38%
BET	**1,10**	-4,27%	-4,29%	-4,38%	-4,42%	-3,69%	-3,72%	-3,81%	-3,83%
	1,50	7,11%	7,16%	7,29%	7,36%	6,16%	6,19%	6,35%	6,39%
	1,75	14,23%	14,31%	14,59%	14,72%	12,31%	12,39%	12,70%	12,78%

Table 5.24 Driving profile coefficient variations analysis (rigid 4x2)

Driving profile coefficient variations analysis – Percentage variations of TCO (rigid 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**1,10**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,50	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	1,75	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**1,10**	-0,25%	-0,25%	-0,25%	-0,24%	-0,20%	-0,19%	-0,19%	-0,19%
	1,50	0,41%	0,41%	0,41%	0,41%	0,33%	0,32%	0,32%	0,32%
	1,75	0,83%	0,82%	0,82%	0,81%	0,65%	0,65%	0,64%	0,63%
FCET 700 bar	**1,10**	-0,26%	-0,26%	-0,26%	-0,26%	-0,20%	-0,20%	-0,20%	-0,20%
	1,50	0,43%	0,43%	0,43%	0,43%	0,34%	0,34%	0,34%	0,34%
	1,75	0,87%	0,86%	0,86%	0,86%	0,68%	0,68%	0,68%	0,67%
FCET LH$_2$	**1,10**	-0,12%	-0,12%	-0,12%	-0,12%	-0,08%	-0,08%	-0,08%	-0,07%
	1,50	0,21%	0,20%	0,20%	0,19%	0,13%	0,13%	0,13%	0,12%
	1,75	0,41%	0,40%	0,39%	0,38%	0,26%	0,26%	0,25%	0,24%
BET	**1,10**	-3,14%	-3,16%	-3,22%	-3,25%	-2,64%	-2,65%	-2,72%	-2,73%
	1,50	5,24%	5,27%	5,37%	5,41%	4,40%	4,42%	4,53%	4,55%
	1,75	10,48%	10,54%	10,74%	10,83%	8,80%	8,84%	9,06%	9,10%

This parameter mostly affects BETs, whereas FCETs are almost not changed (the maximum increases are for FCET at 350 and 700 bar with around 1,8-1,9% in 2023). For BET, when this coefficient is equal to 1,75 the TCO increases by an average value of 17,76% for tractor 4x2, 13,50% for rigid 6x2, and 9,80% for rigid 4x2. FCET LH$_2$ is the technology less affected by the driving profile coefficient (<1%).

5.6 Market maturity

The market maturity is an important parameter related to the number of vehicle sold (2.1.3) and it is assumed the same for all typologies. The situation in “standard conditions” is represented in Table 2.20.

In this analysis two different situations are studied:

- The first is the worst situation in which until 2030 the maturity of the alternative technologies is set as "niche" market maturity, whereas from 2031 to 2040 the maturity is set as "rather niche" market:

Table 5.25 Market maturity in scenario 1

Market maturity in scenario 1					
	2023 - 2026	**2027 - 2030**	**2031 - 2034**	**2035 - 2038**	**2039 - 2040**
Diesel	Mass	Mass	Mass	Mass	Mass
FCET 350 bar	Niche	Niche	Rather niche	Rather niche	Rather niche
FCET 700 bar	Niche	Niche	Rather niche	Rather niche	Rather niche
FCET LH_2	Niche	Niche	Rather niche	Rather niche	Rather niche
BET	Niche	Niche	Rather niche	Rather niche	Rather niche

- The second one is the best scenario in which starting from 2023 all the technologies can be assumed as "mass" market maturity:

Table 5.26 Market maturity in scenario 2

Market maturity in scenario 2					
	2023 - 2026	**2027 - 2030**	**2031 - 2034**	**2035 - 2038**	**2039 - 2040**
Diesel	Mass	Mass	Mass	Mass	Mass
FCET 350 bar	Mass	Mass	Mass	Mass	Mass
FCET 700 bar	Mass	Mass	Mass	Mass	Mass
FCET LH_2	Mass	Mass	Mass	Mass	Mass
BET	Mass	Mass	Mass	Mass	Mass

In the following tables are evaluated and analysed all the percentage variations of the TCO according to the two scenarios above described:

Table 5.27 Market maturity variations analysis (tractor 4x2)

Market maturity variations analysis – Percentage variations of TCO (tractor 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Scenario 2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,88%	6,91%	6,97%	7,00%
	Scenario 2	-12,07%	-12,11%	-12,15%	-12,22%	-6,23%	-6,25%	-6,25%	-6,25%
FCET 700 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,78%	6,78%	6,82%	6,84%
	Scenario 2	-11,82%	-11,87%	-11,93%	-12,00%	-6,08%	-6,13%	-6,15%	-6,17%
FCET LH_2	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,35%	6,39%	6,47%	6,51%
	Scenario 2	-10,53%	-10,59%	-10,67%	-10,76%	-5,17%	-5,20%	-5,21%	-5,23%
BET	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	14,47%	14,72%	14,96%	15,24%
	Scenario 2	-22,66%	-22,81%	-23,25%	-23,55%	-13,24%	-13,27%	-13,68%	-13,93%

Table 5.28 Market maturity variations analysis (rigid 6x2)

Market maturity variations analysis – Percentage variations of TCO (rigid 6x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Scenario 2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,47%	6,49%	6,54%	6,57%
	Scenario 2	-11,14%	-11,17%	-11,20%	-11,26%	-5,56%	-5,57%	-5,57%	-5,56%
FCET 700 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,35%	6,36%	6,39%	6,41%
	Scenario 2	-10,90%	-10,94%	-10,98%	-11,04%	-5,43%	-5,46%	-5,46%	-5,48%
FCET LH_2	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	6,05%	6,08%	6,16%	6,20%
	Scenario 2	-9,95%	-10,01%	-10,08%	-10,17%	-4,81%	-4,83%	-4,84%	-4,86%
BET	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	10,82%	10,99%	11,17%	11,35%
	Scenario 2	-17,53%	-17,63%	-17,97%	-18,20%	-9,91%	-9,91%	-10,21%	-10,38%

Table 5.29 Market maturity variations analysis (rigid 4x2)

Market maturity variations analysis – Percentage variations of TCO (rigid 4x2)									
		2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Scenario 2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
FCET 350 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	5,62%	5,65%	5,70%	5,74%
	Scenario 2	-9,53%	-9,57%	-9,62%	-9,68%	-4,66%	-4,67%	-4,67%	-4,68%
FCET 700 bar	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	5,52%	5,54%	5,58%	5,61%
	Scenario 2	-9,32%	-9,37%	-9,42%	-9,49%	-4,54%	-4,57%	-4,58%	-4,60%
FCET LH_2	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	5,30%	5,34%	5,41%	5,46%
	Scenario 2	-8,62%	-8,69%	-8,77%	-8,87%	-4,13%	-4,15%	-4,17%	-4,20%
BET	**Scenario 1**	0,00%	0,00%	0,00%	0,00%	7,74%	7,85%	7,97%	8,09%
	Scenario 2	-12,91%	-12,98%	-13,23%	-13,39%	-7,08%	-7,07%	-7,28%	-7,39%

As it is possible to see from the tables above, the TCO of Diesel trucks does not change because it was already considered a technology with a "mass" market maturity. For all the other technologies both scenarios change in a significant way the TCO (except in 2023-2026 for 1st scenario because it was already considered as "niche" market maturity). By analysing the 2nd scenario, the most influenced technology is BET with a reduction of more than 20% in 2023 for tractor 4x2 and a reduction of almost 13% in 2023 for rigid 4x2. Considering the high values of these reductions, it is probable that applying scenario 2, all technologies reach a TCO of alternative powertrains lower than the TCO of Diesel trucks in 1-2 years, whereas with scenario 1 all technologies take longer to reach the goal.

5.7 Annual mileage

This is the parameter that mainly affects the TCO of a truck because a lot of the input parameters depend on it. Each truck type has its annual mileage, namely tractor 4x2 has an annual mileage of 110.000-200.000 km, rigid 6x2 has an annual mileage of 70.000-110.000 km, and rigid 4x2 has an annual mileage of 10.000-70.000 km. In this section, in addition to understanding how TCO percentage variations are by varying annual mileage, the goal is to find for each truck typology the annual mileage from which alternative powertrains (FCETs and BET) are competitive over Diesel trucks. This information will be used to find the case study to be analysed in the following chapter.

The first analysis is the evaluation of the percentage variations with respect to the base case and to do this has been chosen a variation different for each truck typology according to their annual mileage range:

- For tractor 4x2 has been chosen a variation of ±30.000 km with respect to the base annual mileage (140.000 km);
- For rigid 6x2 has been chosen a variation of ±25.000 km with respect to the base annual mileage (95.000 km);
- For rigid 4x2 has been chosen a variation of ±10.000 km with respect to the base annual mileage (60.000 km).

The following tables summarise the results obtained:

Table 5.30 Annual mileage variations analysis – 1 (tractor 4x2)

Annual mileage variations analysis – Percentage variations of TCO (tractor 4x2)									
	km	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**-30.000**	-20,07%	-20,08%	-20,08%	-20,08%	-20,09%	-20,09%	-20,10%	-20,10%
	+30.000	+20,35%	+20,35%	+20,38%	+20,38%	+20,39%	+20,39%	+20,39%	+20,40%
FCET 350 bar	**-30.000**	-20,58%	-20,52%	-20,47%	-20,41%	-20,28%	-20,21%	-20,14%	-20,07%
	+30.000	+23,55%	+23,51%	+23,48%	+23,44%	+22,44%	+22,39%	+22,33%	+22,27%
FCET 700 bar	**-30.000**	-20,66%	-20,61%	-20,56%	-20,50%	-20,36%	-20,30%	-20,24%	-20,18%
	+30.000	+23,61%	+23,58%	+23,55%	+23,51%	+22,51%	+22,47%	+22,42%	+22,37%
FCET LH_2	**-30.000**	-20,31%	-20,24%	-20,17%	-20,10%	-19,99%	-19,92%	-19,84%	-19,76%
	+30.000	+22,64%	+22,59%	+22,54%	+22,49%	+21,58%	+21,52%	+21,45%	+21,38%
BET	**-30.000**	-27,14%	-27,17%	-27,26%	-27,31%	-26,19%	-26,21%	-26,32%	-26,34%
	+30.000	+34,75%	+34,82%	+35,07%	+35,19%	+33,00%	+33,07%	+33,36%	+33,44%

Table 5.31 Annual mileage variations analysis – 1 (rigid 6x2)

Annual mileage variations analysis – Percentage variations of TCO (rigid 6x2)									
	km	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**-25.000**	-23,78%	-23,78%	-23,78%	-23,79%	-23,79%	-23,80%	-23,80%	-23,81%
	+25.000	+24,14%	+24,15%	+24,19%	+24,19%	+24,20%	+24,20%	+24,20%	+24,21%
FCET 350 bar	**-25.000**	-23,95%	-23,85%	-23,75%	-23,64%	-23,53%	-23,41%	-23,29%	-23,18%
	+25.000	+27,60%	+27,52%	+27,43%	+27,35%	+26,11%	+26,01%	+25,89%	+25,78%
FCET 700 bar	**-25.000**	-24,07%	-23,97%	-23,87%	-23,77%	-23,65%	-23,54%	-23,43%	-23,32%
	+25.000	+27,68%	+27,61%	+27,53%	+27,44%	+26,21%	+26,11%	+26,01%	+25,91%
FCET LH_2	**-25.000**	-23,84%	-23,72%	-23,60%	-23,48%	-23,39%	-23,26%	-23,13%	-23,00%
	+25.000	+26,83%	+26,74%	+26,65%	+26,55%	+25,41%	+25,29%	+25,17%	+25,05%
BET	**-25.000**	-29,81%	-29,80%	-29,84%	-29,84%	-28,58%	-28,55%	-28,58%	-28,54%
	+25.000	+38,19%	+38,23%	+38,43%	+38,52%	+35,84%	+35,85%	+36,06%	+36,08%

Table 5.32 Annual mileage variations analysis – 1 (rigid 4x2)

Annual mileage variations analysis – Percentage variations of TCO (rigid 4x2)									
	km	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	**-10.000**	-14,28%	-14,29%	-14,29%	-14,29%	-14,29%	-14,30%	-14,30%	-14,30%
	+10.000	+14,80%	+14,81%	+14,86%	+14,86%	+14,86%	+14,87%	+14,87%	+14,87%
FCET 350 bar	**-10.000**	-14,22%	-14,12%	-14,03%	-13,93%	-13,87%	-13,77%	-13,66%	-13,56%
	+10.000	+18,26%	+18,20%	+18,13%	+18,07%	+16,66%	+16,57%	+16,49%	+16,40%
FCET 700 bar	**-10.000**	-14,31%	-14,22%	-14,13%	-14,03%	-13,97%	-13,87%	-13,77%	-13,67%
	+10.000	+18,28%	+18,23%	+18,16%	+18,10%	+16,71%	+16,63%	+16,55%	+16,47%
FCET LH_2	**-10.000**	-14,24%	-14,13%	-14,03%	-13,92%	-13,86%	-13,75%	-13,64%	-13,53%
	+10.000	+17,76%	+17,70%	+17,64%	+17,57%	+16,25%	+16,16%	+16,07%	+15,98%
BET	**-10.000**	-17,11%	-17,08%	-17,06%	-17,03%	-16,26%	-16,21%	-16,16%	-16,11%
	+10.000	+22,44%	+22,44%	+22,51%	+22,54%	+20,73%	+20,70%	+20,77%	+20,74%

By analysing these results, it is possible to see that the annual mileage affect significantly the TCO. The technology mostly influenced by this parameter is BET, followed by FCETs technologies. In tractor 4x2 and rigid 6x2 typologies, BET undergoes to a variation of about ±33-38%, whereas for rigid 4x2 the variations are around ±20-22% (due to a lower annual mileage variation). For all the other technologies, the variation is in the order of ±20-28% for the first two truck types, whereas is around ±14-18% for rigid 4x2 trucks.

Regarding the number of years necessary to reach the goal as a function of the annual mileage, in the following tables are summarised the results obtained from the model:

Table 5.33 Annual mileage variations analysis – 2 (tractor 4x2)

Annual mileage variations analysis – Number of years to reach the goal (tractor 4x2)										
	200.000	**190.000**	**180.000**	**170.000**	**160.000**	**150.000**	**140.000**	**130.000**	**120.000**	**110.000**
FCET 350 bar	2027	2027	2027	2027	2027	2027	2026	2026	2026	2026
FCET 700 bar	2027	2027	2027	2027	2027	2027	2027	2027	2027	2027
FCET LH_2	2027	2027	2027	2027	2027	2027	2027	2027	2027	2027
BET	-	2035	2035	2031	2031	2031	2030	2029	2029	2028

This analysis is carried out by varying the annual mileage in the interval in which this truck type is used (110.000-200.000 km). By looking the values in the table, it is possible to note that the only technology affected by this variation is BET, whereas FCETs are not influenced by the annual mileage (except for FCET at 350 bar than has a little improvement with an annual mileage lower than 140.000 km). Compared to the base case (140.000 km), by increasing the annual mileage the number of years necessary to achieve a TCO lower than the one of Diesel trucks is the same for all FCETs, whereas is higher for BET (with an annual mileage equal to 200.000 km it does not achieve the goal). On the other hand, by reducing this parameter the number of years necessary is reduced for BET ("only" 5 years if the annual mileage is 110.000 km), whereas for all FCETs it is always the same (4 years), except for FCET at 350 bar in which if the annual mileage is lower than 140.000 km the number of years needed is 3 years.

Table 5.34 Annual mileage variations analysis – 2 (rigid 6x2)

Annual mileage variations analysis – Number of years to reach the goal (rigid 6x2)									
	110.000	**105.000**	**100.000**	**95.000**	**90.000**	**85.000**	**80.000**	**75.000**	**70.000**
FCET 350 bar	2026	2026	2026	2026	2026	2026	2026	2026	2026
FCET 700 bar	2027	2027	2027	2027	2027	2027	2027	2027	2027
FCET LH_2	2027	2027	2027	2027	2027	2027	2027	2027	2027
BET	2027	2027	2027	2027	2027	2027	2027	2027	2027

For trucks rigid 6x2 the range in which it is possible to varying the annual mileage is between 70.000 and 110.000 km, and the base case assumes 95.000 km as reference annual mileage. In contrast to the previous case, by varying the annual mileage the number of years necessary to achieve a TCO of alternative technologies lower than the TCO of conventional trucks is the same (3 years for FCET at 350 bar and 4 years for FCET at 700 bar, FCET LH_2, and BET).

Table 5.35 Annual mileage variations analysis – 2 (rigid 4x2)

Annual mileage variations analysis – Number of years to reach the goal (rigid 4x2)							
	70.000	**60.000**	**50.000**	**40.000**	**30.000**	**20.000**	**10.000**
FCET 350 bar	2025	2026	2026	2026	2026	2027	2027
FCET 700 bar	2026	2026	2026	2027	2027	2027	2027
FCET LH_2	2026	2026	2027	2027	2027	2027	2027
BET	2027	2025	2024	2023	2023	2023	2023

For this type of truck, rigid 4x2, the annual mileage ranges between 10.000 km and 70.000 km (the reference value for the model is 60.000 km) and it is used for short-haul segment. From the analysis of the values in Table 5.35, for FCETs it is possible to see an increasing of the number of years needed to achieve the goal by reducing the annual mileage, particularly for FCET at 350 bar the number of years changes from 2 years (for annual mileage between 30.000 km and 70.000 km) to 4 years (for annual mileage between 10.000 km and 20.000 km), for FCET at 700 bar it changes from 3 years (for annual mileage between 50.000 km and 70.000 km) to 4 years (for annual mileage between 10.000 km and 40.000 km), and for FCET LH_2 it changes from 3 years (for annual mileage between 60.000 km and 70.000 km) to 4 years (for annual mileage between 10.000 km and 50.000 km). For BET the trend is opposite, so by increasing the annual mileage also the number of years increases: with 70.000 km/year it achieves the goal in 4 years, whereas for annual mileage lower than 50.000 km already from 2023 the TCO is lower than the one of Diesel trucks, so it is competitive already in the current market.

5.8 Possible combinations

In the previous sections it was analysed how each parameter affects the TCO by evaluating a percentage variation compared to the TCO obtained without changing these parameters with respect to the value studied in chapter 3. This analysis was carried out without considering the number of years needed to achieve a lower TCO for alternative engines than diesel trucks, so in this section some possible combinations of these parameters are studied, knowing their effects on TCO, useful to achieve the goal as soon as possible. Some of the results obtained from these analyses are successively used in the case study studied in the following chapter.

The possible combinations analysed in this section are three: a first combination, that is the more optimistic one, in which all parameters are chosen in order to achieve the goal in the lowest number of years, the second combination is another optimistic case, whereas the last one is a more realistic case in which no incentives are applied to alternative powertrains, but Diesel truck are surcharged.

The parameters used in the three cases are reported in the Table 5.36:

Table 5.36 Parameters combinations for the three cases

Parameters combinations for the three cases				
		Optimistic case 1	**Optimistic case 2**	**Realistic case**
Country		Italy	Italy	Italy
Motor vehicle tax	Diesel	+ 100 %	+ 50 %	+ 50 %
	Others	0,00 €	- 50 %	0 %
Registration fee	Diesel	+ 100 %	+ 50 %	+ 50 %
	Others	0,00 €	- 50 %	0 %
Road toll	Diesel	+ 100 %	+ 50 %	+ 50 %
	Others	0,00 €/km	- 50 %	0 %
Energy/Fuel cost	Diesel	+ 100 % of taxations	+ 50 % of taxations	+ 50 % of taxations
	Others	NO taxations	- 50 % of taxations	+ 0,00 % of taxations
Driving profile coefficient		Homogeneous (1,10)	Rather homog. (1,25)	Rather homog. (1,25)
Market maturity	2023-2026	Mass	Rather niche	Rather niche
	2027-2030	Mass	Rather mass	Rather mass
	2031-2034	Mass	Mass	Mass
	2035-2038	Mass	Mass	Mass
	2039-2040	Mass	Mass	Mass
Annual mileage	Tractor 4x2	110.000 km/year	110.000 km/year	110.000 km/year
	Rigid 6x2	95.000 km/year	95.000 km/year	95.000 km/year
	Rigid 4x2	40.000 km/years	40.000 km/years	40.000 km/years

5.8.1 First combination – Optimistic case 1

This combination of parameters is the more optimistic (case 1) because the values of these parameters are chosen in order to have a huge difference between Diesel and alternative trucks. For conventional trucks, motor vehicle tax, registration fee, and road toll are twice with respect to the reference values, whereas for alternative powertrains is considered that they are exempt from paying these fees. Fuel tax is also double in the case of diesel trucks, whereas it is not considered for FCETs and BET. With these assumptions, and with all the other assumptions reported in Table 5.36, the TCO obtained from the model are the following:

Table 5.37 TCO of optimistic case 1 (tractor 4x2)

TCO of optimistic case 1 [€/truck] (tractor 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	1.524.053	1.533.202	1.544.318	1.553.115	1.561.737	1.570.182	1.578.451	1.586.544
FCET 350 bar	574.770	556.039	538.437	521.999	505.924	490.946	476.210	462.644
FCET 700 bar	576.269	557.530	539.809	523.309	507.226	492.187	477.390	463.763
FCET LH_2	564.887	546.489	529.162	512.995	497.243	482.532	468.059	454.701
BET	519.036	515.497	511.978	508.477	486.840	483.484	480.147	475.199

Table 5.38 TCO of optimistic case 1 (rigid 6x2)

TCO of optimistic case 1 [€/truck] (rigid 6x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	1.149.606	1.155.088	1.161.977	1.167.154	1.172.180	1.177.053	1.181.775	1.186.344
FCET 350 bar	439.168	425.826	413.285	401.583	390.152	379.523	369.067	359.443
FCET 700 bar	440.099	426.750	414.135	402.393	390.956	380.289	369.794	360.132
FCET LH_2	433.033	419.904	407.541	396.014	384.790	374.333	364.046	354.557
BET	380.624	378.122	375.635	373.162	358.169	355.815	353.476	350.147

Table 5.39 TCO of optimistic case 1 (rigid 4x2)

TCO of optimistic case 1 [€/truck] (rigid 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	515.530	517.566	520.281	522.189	524.033	525.813	527.529	529.181
FCET 350 bar	211.817	206.632	201.748	197.197	192.748	188.624	184.556	180.810
FCET 700 bar	212.009	206.823	201.924	197.364	192.914	188.782	184.706	180.952
FCET LH_2	210.551	205.410	200.564	196.049	191.644	187.555	183.523	179.805
BET	161.628	161.004	160.383	159.765	154.428	153.852	153.280	152.501

In this optimistic case, in which no taxes are applied for alternative powertrains whereas to Diesel trucks are applied double taxes, from 2023 all alternative trucks have a TCO lower than the one of conventional trucks. For all truck typologies, the best technology is the electric one (BET) with TCO of around one-third of the TCO of Diesel powertrains. In particular, for tractor 4x2 the TCO of BET is 34% of the one of Diesel trucks, for rigid 6x2 is 33% of the TCO of Diesel trucks, and for rigid 4x2 is 31% of the TCO of conventional trucks. In 2023, the results obtained for FCET technologies are almost the same for each of them, with a value of around 570.000 €/truck for tractor 4x2, around 435.000 €/truck for rigid 6x2, and around 211.000 €/truck for rigid 4x2.

5.8.2 Second combination – Optimistic case 2

This second case is the one in which the combination of the input parameters is again optimistic for a future in which the taxes are not the same for all technologies but are higher for Diesel trucks than for alternative powertrains (but they are not tax-free). Also, the road toll is paid for both alternative and conventional trucks, even if the amount to pay is different for these two trucks categories.

All the assumptions done for this case are summarised in Table 5.36, and the results are reported in the following tables:

Table 5.40 TCO of optimistic case 2 (tractor 4x2)

TCO of optimistic case 2 [€/truck] (tractor 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	1.282.901	1.289.259	1.297.629	1.303.724	1.309.686	1.315.517	1.321.215	1.326.782
FCET 350 bar	879.562	843.525	810.178	778.654	716.982	690.148	664.163	640.443
FCET 700 bar	901.417	864.372	830.091	798.079	735.922	707.870	681.721	656.863
FCET LH_2	901.380	860.996	823.475	788.261	726.147	696.612	668.078	642.204
BET	935.892	921.619	897.213	881.338	773.692	760.507	737.423	724.533

Table 5.41 TCO of optimistic case 2 (rigid 6x2)

TCO of optimistic case 2 [€/truck] (rigid 6x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	968.816	972.492	977.614	981.063	984.397	987.618	990.724	993.717
FCET 350 bar	659.945	634.421	610.822	588.524	544.861	525.889	507.533	490.786
FCET 700 bar	675.143	648.885	624.600	601.933	557.906	538.079	519.597	502.050
FCET LH_2	676.748	648.125	621.546	596.618	552.382	531.487	511.310	493.031
BET	667.917	657.675	640.511	629.341	560.089	550.724	534.635	525.518

Table 5.42 TCO of optimistic case 2 (rigid 4x2)

TCO of optimistic case 2 [€/truck] (rigid 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	436.036	437.380	439.419	440.667	441.867	443.019	444.123	445.179
FCET 350 bar	299.304	289.440	280.334	271.720	254.777	247.430	240.314	233.824
FCET 700 bar	305.086	294.919	285.521	276.747	259.647	251.978	244.819	238.023
FCET LH_2	308.062	296.929	286.586	276.880	259.343	251.194	243.303	236.168
BET	258.271	254.728	248.687	244.992	227.042	223.783	218.101	214.937

As for the optimistic case 1, in this case all technologies achieve a TCO lower than the TCO of Diesel trucks in 2023. The best technology is again, for all truck typologies, BET with TCO of around two-third of the TCO of Diesel powertrains. In particular, in 2023, for tractor 4x2 the TCO of BET is 73% of the one of Diesel trucks, for rigid 6x2 is 69% of the TCO of Diesel trucks, and for rigid 4x2 is 59% of the TCO of conventional trucks.

5.8.3 Third combination – Realistic case

This last case is the one in which Diesel trucks are surcharged for both motor vehicle tax, registration fee, road tool, and fuel cost. The assumptions done are in Table 5.36 and the obtained results are the following:

Table 5.43 TCO of realistic case (tractor 4x2)

TCO of realistic case [€/truck] (tractor 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	1.282.901	1.289.259	1.297.629	1.303.724	1.309.686	1.315.517	1.321.215	1.326.782
FCET 350 bar	1.118.576	1.068.352	1.021.971	978.050	905.103	867.609	831.569	798.876
FCET 700 bar	1.160.709	1.108.354	1.059.927	1.014.915	940.887	901.092	864.794	829.899
FCET LH_2	1.180.949	1.121.611	1.066.341	1.014.564	937.553	894.266	852.620	815.239
BET	1.195.817	1.171.952	1.129.704	1.104.477	987.574	965.229	924.928	903.117

Table 5.44 TCO of realistic case (rigid 6x2)

TCO of realistic case [€/truck] (rigid 6x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	968.816	972.492	977.614	981.063	984.397	987.618	990.724	993.717
FCET 350 bar	836.154	800.527	767.654	736.548	684.882	658.354	632.882	609.789
FCET 700 bar	865.570	828.404	794.050	762.139	709.677	681.524	655.847	631.197
FCET LH_2	881.393	839.292	800.109	763.436	708.646	678.020	648.581	622.179
BET	858.788	841.641	811.819	793.949	718.080	702.180	673.968	658.521

Table 5.45 TCO of realistic case (rigid 4x2)

TCO of realistic case [€/truck] (rigid 4x2)								
	2023	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Diesel	436.036	437.380	439.419	440.667	441.867	443.019	444.123	445.179
FCET 350 bar	372.527	358.678	345.914	333.827	313.731	303.407	293.489	284.502
FCET 700 bar	383.889	369.418	356.048	343.629	323.203	312.254	302.261	292.669
FCET LH_2	392.445	375.997	360.686	346.354	324.660	312.680	301.145	290.814
BET	337.248	330.972	319.942	313.599	293.036	287.197	276.749	271.091

As highlight from the tables above, even in this case in 2023 all alternative trucks achieve the goal of a TCO lower than the one of Diesel powertrain, but with a lower gap (for example, for tractor 4x2 the gap between Diesel and BET trucks is of around 87.084 €, only 6,8% of the TCO of Diesel truck). BET is always the best technology for rigid 4x2, whereas for tractor 4x2 and rigid 6x2 is the worst solution between alternative powertrains (for rigid 6x2 only in 2023 is better than FCET at 700 bar and FCET LH_2).

5.9 Final considerations

By summarising all the above results obtained from these analyses it is possible to highlight these points:

- In terms of country, the best one is Greece, whereas the worst country is the United Kingdom (mainly for the high road toll imposed by the Government);

- Motor vehicle tax and registration fee do not affect significantly the TCO because they are fix values and they do not depend on annual mileage: the percentage variation is at least ± 0,83%;
- In the first case analysed, road toll affects the results by at least ± 3,06% up to a maximum of ± 6,03% for truck rigid 6x2, which presents the highest variations. In the second case, the one in which only Diesel trucks are subjected to road toll, the variations for alternative powertrains are higher than the previous case, with values until -12% in 2030, but with an average value, for all typology, of around -9%.
- The variations in the energy/fuel cost are higher in 2023 than in other years, whereas in 2030 they reach the lowest values. For BETs, the cost of energy mostly changes for short-haul segment (rigid 4x2) than for long-haul segment (tractor 4x2). Regarding FCETs, the variations are between ±11,13% (for rigid 4x2, in 2030) and ±18,68 % (for tractor 4x2, in 2023).
- The driving profile coefficient principally affects BET technology with an average value of 14% (considering all the three typologies of trucks), whereas for the other alternative powertrains it produces percentage variations lower than 2% independently from the truck typology;
- By considering a more mature market already from 2023 (scenario 2), the number of years needed to reach the goal is lower than the number of years in the base case previously analysed and the reductions are significant, especially for BET technology;
- The annual mileage is the parameter that mostly affects the TCO, with values between ±20% and ±40% for BET, and between ±13% and ±23% for the other alternative powertrains;
- The analysis of the possible combinations of input parameters leads to the consideration that in order to have a lower TCO for alternative powertrains is not mandatory to impose incentives for these vehicles but is sufficient to impose surcharged to the existing Diesel vehicles (realistic case), whereas the application of incentives for alternative trucks leads to a very low TCO compared to that of Diesel trucks. The combination of these two ways to reduce the TCO of alternative trucks over conventional ones (optimistic cases) leads to a very large gap between these technologies.

6. Case study

Heavy-duty trucks are largely used in the transport and logistics industry, so the introduction in the market of new alternative powertrains is an advantage for the sector in order to reduce the greenhouse gas emissions, as establish from the European Union, and to reduce the Total Cost of Ownership. In today's market there are several conventional trucks, but the number of alternative trucks is very low (especially for FCET that are extremely rare today, whereas BET are more widespread). The aim of this chapter is to analyse a case study in order to see the trend of TCO by using actual data in terms of routes and truck characteristics. Particularly, the analysis is made for the long-haul segment truck typology, namely for tractor 4x2.

The country selected for this analysis is Italy, so the route is within the national borders and the daily mileage is evaluated according to the annual mileage and to the number of working days, that is assumed equal to 250 day/year. The annual mileage depends on the truck type, and it is chosen according to the analysis conducted before in order to reach the main goal (TCO of alternative trucks lower than TCO of Diesel trucks) in the lowest number of years as possible. As a result, the annual mileage used in this case study is 110.000 km/year that corresponds to 440 km/day. According to this value, the route selected is the A4 motorway Turin-Trieste, that is 528 km long. Considering that this distance is higher than the daily mileage of this type of truck, this means that the route is partially travelled with a possible stop during this route.

The other parameters that depend on the country are motor vehicle tax, registration fee, road toll, and energy/fuel cost:

- Motor vehicle tax and registration fee are the same imposed by the model because they are chosen according to the country;
- Road toll is calculated on the basis of the actual route of the case study (in the model it is assume as an average value for the country). For the selected route (Turin-Trieste) the paid routes are two, Torino Rondissone-Milano Ghisolfa and Milano Est-Trieste Lisert. The first is 130 km long and costs 35,10 €, the second is 398 km long and costs 63,00 €, then the total cost is 98,10 € for 528 km, that means 0,19 €/km [38];
- Regarding the cost of Diesel, it is used the actual cost (evaluated on July 3rd, 2023) that is 1,685 €/l and the price is expected to increase by 0,02 €/l each year until 2030 [39];

- The cost of hydrogen is the same used in the model both for hydrogen at 350 and 700 bar and for liquid hydrogen;
- The cost of electricity for BET is the same used in the model.

To summarise, the values used in this case study are reported in Table 6.1:

Table 6.1 Parameters related to the country

Parameters related to the country			
Motor vehicle tax		€/year	654,99
Registration fee		€	101,20
Road toll		€/km	0,19
Energy/Fuel cost (in 2023)	**Diesel**	€/l	1,685
	FCET 350 bar	€/kg	6,90
	FCET 700 bar	€/kg	7,30
	FCET LH_2	€/kg	7,70
	BET	€/kWh	0,30

The parameters related to the truck are CO_2 emissions, share of empty runs, and payload (related to the payload there is the consumption of the truck). So, in order to define the case study, it is necessary to define these parameters: CO_2 emissions for Diesel trucks are assumed to be the same used in the model, the share of empty runs is 25% considering that the majority of the trips are with the truck full (or almost full by considering the loading factor equal to 90%), and the maximum payload of the truck for this case study is 25 tonnes, so by considering all the weight reduction describe in the dedicated section, the net payload is reported in Table 6.2 with all the other parameters related to the truck:

Table 6.2 Parameters related to the truck

Parameters related to the truck			
CO_2 emissions		gCO_2/l	3.286,53
Share of empty runs		%	25 %
Net payload (in 2023)	**Diesel**	t	16,88
	FCET 350 bar	t	18,22
	FCET 700 bar	t	17,97
	FCET LH_2	t	18,62
	BET	t	15,98
Consumption (in 2023)	**Diesel**	l/km	0,309
	FCET 350 bar	kg/km	0,081
	FCET 700 bar	kg/km	0,081
	FCET LH_2	kg/km	0,081
	BET	kWh/km	1,349

Finally, with the specific values for the case study the outputs of the model are obtained and commented in the following sections. The analysis of the results is done by considering the three outputs of the model: TCO in €/truck, TCO in c€/t-km, and CO_2 emissions in gCO_2/t-km. All the analyses and considerations are about combined 1st and 2nd life of the truck.

6.1 TCO in €/truck

The output of the TCO evaluated in €/truck is first broken down into its components, in order to analysed which components affect the result most, then it is compared over the years to understand when begins the competitiveness of alternative powertrains compared to Diesel trucks. By analysing only some years (2023, 2027, and 2030), the components of the TCO of the five technologies are reported in the following tables:

Table 6.3 TCO for Diesel truck [€/truck]

Diesel truck [€/truck]			
Items	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000
Diesel powertrain	24.000	26.500	26.500
Diesel consumption	651.849	667.265	677.903
Ad-Blue consumption	13.540	13.232	13.001
Registration fee	101	101	101
Motor vehicle tax	6.550	6.550	6.550
Insurance	13.050	13.425	13.425
Maintenance	132.000	132.000	132.000
Infrastructure	0	0	0
Road toll	209.000	209.000	209.000
Residual value	7.029	7.761	7.761
TCO	**1.106.061**	**1.123.312**	**1.133.720**

Table 6.4 TCO for FCET 350 and 700 bar [€/truck]

	FCET 350 bar [€/truck]			FCET 700 bar [€/truck]		
Items	**2023**	**2027**	**2030**	**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	63.000	63.000	63.000
E-Drive powertrain	37.401	19.650	18.871	37.401	19.650	18.871
FC module	103.200	44.880	37.200	103.200	44.880	37.200
H_2 tank	47.533	30.770	26.996	51.443	33.010	29.521
Small battery	46.389	33.390	32.625	46.389	33.390	32.625
H_2 consumption	699.574	536.029	438.081	740.129	569.717	467.287
Registration fee	101	101	101	101	101	101
Motor vehicle tax	6.550	6.550	6.550	6.550	6.550	6.550
Insurance	44.628	28.753	26.804	45.215	29.090	27.183
Maintenance	121.000	121.000	121.000	121.000	121.000	121.000
Infrastructure	0	0	0	0	0	0
Road toll	209.000	209.000	209.000	209.000	209.000	209.000
Residual value	64.947	35.270	31.760	65.785	35.750	32.301
TCO	**1.313.429**	**1.057.853**	**948.468**	**1.357.643**	**1.093.637**	**980.036**

Table 6.5 TCO for FCET LH_2 and BET [€/truck]

	FCET LH_2 [€/truck]				BET [€/truck]		
Items	**2023**	**2027**	**2030**		**2023**	**2027**	**2030**
Chassis	63.000	63.000	63.000	Chassis	63.000	63.000	63.000
E-Drive powertrain	37.401	19.650	18.871	Large battery cost	630.225	444.320	425.757
FC module	103.200	44.880	37.200	Energy consumption	506.430	395.928	324.180
H_2 tank	24.812	12.848	10.617	Registration fee	101	101	101
Small battery	46.389	33.390	32.625	Motor vehicle tax	6.550	6.550	6.550
H_2 consumption	780.684	582.597	467.287	Insurance	103.984	76.098	73.313
Registration fee	101	101	101	Maintenance	121.000	121.000	121.000
Motor vehicle tax	6.550	6.550	6.550	Infrastructure	0	0	0
Insurance	41.220	26.065	24.347	Road toll	209.000	209.000	209.000
Maintenance	121.000	121.000	121.000	Residual value	184.566	130.122	124.686
Infrastructure	0	0	0				
Road toll	209.000	209.000	209.000				
Residual value	60.078	31.430	28.250				
TCO	**1.373.278**	**1.087.652**	**962.348**	**TCO**	**1.455.724**	**1.185.875**	**1.098.216**

For the Diesel truck almost 60% of the TCO is due to the fuel cost, followed by the road toll that cover the 19% of the total cost. For this conventional technology, the TCO increases over years, mainly due to the Diesel cost that increases every year as explained in the previous section. From 2023 to 2030 the TCO increases by 2,5%.

Compared to Diesel truck, all FCET technologies have a TCO higher in 2023, although in the following years it achieve values lower than the one of conventional truck. The most important contribute is due to the hydrogen consumption cost, that is 53-57% in 2023, 51-54% in 2027, and 46-49% in 2030. Regarding BET, its TCO is the highest in 2023 and 2027, and the most important contributions are due to both large battery cost and energy consumption cost which a contribute, in 2023, by 43% and 35%, respectively.

The second analysis about the TCO expressed in €/truck regards the number of years necessary to be competitive in the market compared to Diesel trucks. In order to understand when the competitiveness starts, all the results from 2023 to 2040 are analysed and compared.

The results are reported in the following table:

Table 6.6 TCO of tractor 4x2 [€/truck]

TCO of tractor 4x2 [€/truck]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	1.106.061	1.313.429	1.357.643	1.373.278	1.455.724
2024	1.109.970	1.260.359	1.302.242	1.311.108	1.429.150
2025	1.115.934	1.211.150	1.250.728	1.252.963	1.386.124
2026	1.119.667	1.164.975	1.203.266	1.198.884	1.362.014
2027	1.123.312	**1.057.853**	**1.093.637**	**1.087.652**	1.185.875
2028	1.126.869	1.019.300	1.053.028	1.043.382	1.161.205
2029	1.130.339	982.106	1.015.758	1.000.537	**1.122.329**
2030	1.133.720	948.468	980.036	962.348	1.098.216
2031	1.133.720	919.489	950.451	935.973	1.024.117
2032	1.133.720	919.101	950.063	935.707	1.024.117
2033	1.133.720	918.653	949.676	935.440	1.024.117
2034	1.133.720	918.266	949.228	935.174	1.024.117
2035	1.133.720	897.586	928.003	918.250	979.658
2036	1.133.720	897.465	927.822	918.190	979.658
2037	1.133.720	897.078	927.495	917.924	979.658
2038	1.133.720	896.957	927.374	917.863	979.658
2039	1.133.720	896.630	926.986	917.657	979.658
2040	1.133.720	896.509	926.865	917.597	979.658

The results in the table above show that FCETs are more competitive than BET and that the number of years necessary to achieve a TCO lower than the one of conventional trucks is 4 (2027), whereas for BET is 6 (2029). The three hydrogen-powered truck technologies have similar results in terms of TCO, although the best one is the FCET at 350, followed by FCET LH_2 and FCET at 700 bar. By considering percentage estimations of the results compared to 2023, in 2040 the TCO is around 68% for FCET at 350 and 700 bar and around 67% for FCET LH_2 and BET.

Figure 6.1 shows the trends over the years for the different technology:

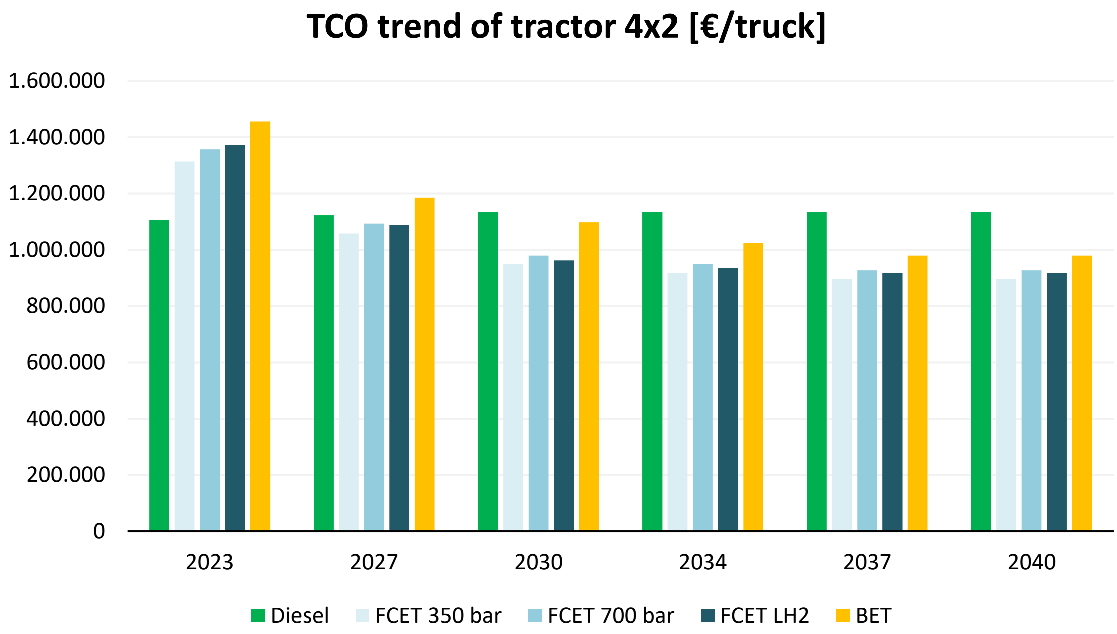

Figure 6.1 TCO trend of tractor 4x2 [€/truck]

6.2 TCO in c€/t-km

The second output of the model is the TCO in c€/t-km and the results are summarised in Table 6.7:

Table 6.7 TCO of tractor 4x2 [c€/t-km]

TCO of tractor 4x2 [c€/t-km]					
	Diesel	**FCET 350 bar**	**FCET 700 bar**	**FCET LH_2**	**BET**
2023	5,17	5,72	5,99	5,86	7,38
2024	5,19	5,49	5,74	5,59	7,23
2025	5,22	5,27	5,51	5,35	7,01
2026	5,24	**5,06**	5,29	**5,11**	6,77
2027	5,25	4,59	**4,80**	4,62	5,81
2028	5,27	4,41	4,61	4,43	5,62
2029	5,29	4,24	4,44	4,24	5,37
2030	5,30	4,09	4,28	4,07	**5,20**
2031	5,30	3,97	4,15	3,96	4,85
2032	5,30	3,97	4,15	3,96	4,85
2033	5,30	3,96	4,15	3,96	4,85
2034	5,30	3,96	4,15	3,96	4,85
2035	5,30	3,87	4,05	3,89	4,64
2036	5,30	3,87	4,05	3,89	4,64
2037	5,30	3,87	4,05	3,88	4,64
2038	5,30	3,87	4,05	3,88	4,64
2039	5,30	3,87	4,05	3,88	4,64
2040	5,30	3,87	4,05	3,88	4,64

The results follow the same trend of the previous output, with BET technology that is the worst one, whereas FCET at 350 bar is again the best technology with FCET LH_2. In 2040 the percentage reduction of the TCO is around 33% for all hydrogen trucks, whereas is 37% for BET.

6.3 CO_2 emission in gCO_2/t-km

The CO_2 emissions are exclusively due to Diesel trucks and the results obtained are reported in Table 6.8:

Table 6.8 CO_2 emissions of Diesel truck [gCO_2/t-km]

CO_2 emissions of Diesel truck [gCO_2/t-km]	
2023	59,46
2024	59,12
2025	58,78
2026	58,44
2027	58,10
2028	57,77
2029	57,43
2030	57,09
2031	57,09
2032	57,09
2033	57,09
2034	57,09
2035	57,09
2036	57,09
2037	57,09
2038	57,09
2039	57,09
2040	57,09

The value decreases over years until 2030 and then it is constant because it depends on the well to wheel emissions that is a constant value, on the consumption that varies until 2030, and on the net payload that again varies until 2030. The reduction is due to improvements in engine efficiency, but it is very low (around 4%).

6.4 Final considerations

By summarising the results of this case study, it is possible to point out the following considerations:

- For long-haul segment like this, the electric solution is the worst one and its competitiveness in the market with the conventional truck starts after 6 years (2029);
- FCET technologies are comparable each other, although FCET at 350 bar is slightly better than the others in terms of TCO in €/truck;

- The CO_2 emissions of Diesel truck in this route in around 60 gCO_2/t-km in 2023 and this value decreases over the years thanks to technological improvements especially in engine efficiency: in 2030 the value of CO_2 emissions is 4% lower than the value in 2023.

7. Conclusions

The model aims to study the feasibility to replace Diesel trucks with alternative trucks powered by hydrogen and electricity, and to do this an analysis of the TCO is carried out. In this model, the base assumption in order to do this cost estimation is that the FCET technology is not in the early stage, but it is an advanced stage with respect the actual situation. Nowadays, for example, to produce and buy 1 kg of green hydrogen is very expensive and a refuelling station system for hydrogen trucks is not present in Europe (except for some single refuelling stations in the European area).

By using the reference input parameters described and commented in chapter 2, the obtained numbers of years necessary to achieve a TCO for alternative trucks lower than the TCO of conventional trucks are reported in Table 7.1:

Table 7.1 Summary of the results

Summary of the results						
	Tractor 4x2		Rigid 6x2		Rigid 4x2	
	TCO in €/truck	TCO in c€/t-km	TCO in €/truck	TCO in c€/t-km	TCO in €/truck	TCO in c€/t-km
FCET 350 bar	2026	2025	2026	2023	2026	2023
FCET 700 bar	2027	2026	2027	2024	2026	2023
FCET LH_2	2027	2025	2027	2024	2026	2023
BET	2030	2031	2027	2027	2025	2023

The results are reported in two different ways: the first is considering TCO evaluated in €/truck, whereas the second is considering TCO calculated in c€/t-km, so by estimating the cost of transporting one tonne payload for one kilometre of the route. The two results are different and lead to a two different perspectives: by considering the number of years necessary to obtain a TCO of alternative trucks, evaluated in €/truck, lower than the one of conventional trucks, the result is that this number is always higher than the number of years in the second evaluation.

By considering the first output, for tractor 4x2 it is possible to note that FCETs technologies take 4 years to achieve the goal, whereas BETs take 7 years. This last technology presents the best improvement by analysing the other two truck typologies: for rigid 6x2 the number of years is 4, whereas for rigid 4x2 the number of years is only 2. These results lead to the conclusion that electric trucks are the best solution only for short-haul segment, so by decreasing the annual mileage its competitiveness increases. FCETs present almost the same trends for every truck typology, in which they take 3-4 years to achieve the goal.

By analysing the second result of the model, the number of years if the TCO is evaluated in c€/t-km, the situation changes: the number of years needed to achieve the goal is lower for every typology and for every technology (except for BET for tractor 4x2). For rigid 4x2, the truck typology with the lowest annual mileage, the competitiveness of alternative powertrains begins in 2023 for all trucks, whereas for rigid 6x2 it begins in 2023 only for FCET at 350 bar.

From these results obtained with the base assumption mentioned above, the conclusion is that to anticipate the competitiveness of alternative trucks in the market both market improvements and Government's incentives are needed, as point out in chapter 5. The parameters that most affect the TCO are the market maturity, the road toll, and the energy/fuel cost. Also, the annual mileage of the trucks affects the result in a significant way, but this parameter does not depend on external factors as Governments or market. Road toll variation leads to a change in TCO of around 3-6%, whereas incentives on energy/fuel taxation can have a significant effect on the TCO, with a reduction of 11-19% if these taxes are reduced of 50%. The market maturity is another important aspect of the TCO: the difference between considering niche market maturity and mass market maturity (in 2023) leads to a variation until 23% on the TCO, and this variation is more important in BET technology than in FCET technologies.

The analysis of the possible combinations of input parameters leads to the consideration that in order to have a lower TCO for alternative powertrains is not mandatory to impose incentives for these vehicles but is sufficient to impose surcharged to the existing Diesel vehicles, whereas the application of incentives for alternative trucks leads to a very low TCO compared to that of Diesel trucks.

All these incentives and all the contributions of the Governments are one of the possible ways to achieve the European goals and to achieve carbon neutrality in 2050 by working on the transport sector, which is one of the sectors that emits most GHG, but before to work on these incentives and contributions of the Governments it is necessary to develop and implement a refuelling stations system in all the European countries and it is necessary to improve the hydrogen production by relying on renewable sources in order to minimise CO_2 emissions.

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