TECHNO-ECONOMIC ANALYSIS OF BIO GAS AND HYDROGEN OPERATED HEAVY DUTY VEHICLES

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Electrical Engineering
In co-operation with Hebei University of Technology

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Due to rising environmental awareness and improved renewable energy sources, biogas and hydrogen fuel applications in heavy-duty transport vehicles (HDVs) are increasingly being considered. The main objective of this study is to extend the analysis of the total cost per kilometre of the vehicle using biogas and hydrogen fuel and to compare the results with those of diesel vehicles. The total cost per kilometre is further analyzed with the help of the total distance covered by the vehicle in a year, the fuel consumption, and the number of hydrogen and biogas refuelling stations along the route, and comparing it with diesel-powered vehicles to provide data to support the choice of a more sustainable transport solution. The results show that diesel vehicles have the lowest total cost of ownership (TCO) per kilometre at €1.24, while biogas vehicles, especially liquefied biogas (LBG), offer a promising alternative with a TCO of €3.73/km. Hydrogen-powered vehicles showed the highest costs, with 350 bar systems reaching €9.17/km due to fuel and infrastructure costs. Sensitivity analysis revealed that improvements in fuel efficiency and reductions in station construction costs could impact hydrogen's competitiveness. The findings suggest that while hydrogen requires further development and investment, biogas is currently the most cost-effective sustainable fuel option for HDVs.

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SYMBOLS AND ABBREVIATIONS

Roman characters

L	Length of the route	km
D_{total}	Total mileage per year	km
D_{daily}	Daily distance per vehicle	km
$D_{operational}$	Operational days per year	
F_{total}	Total fuel consumption per year	
F_{rate}	Fuel consumption rate	kg/100 km or L/100 km
$C_{fuel,t}$	Fuel cost	€/kg, €/L
$N_{station}$	refuelling stations	
N	Number of vehicles	
$R_{vehicle}$	Range of each vehicle per refuelling	km
C_{capex}	Initial investment costs	€
$C_{opex,t}$	Operational costs in year t	€
r	Discount rate	
T	Study period	

Greek characters

ρ	Density	kg/m³
ϕ	Fuel utilization factor	

Subscripts

h	Hydrogen
b	Biogas
d	Diesel
t	Total
f	Fuel
e	Efficiency

Abbreviations

HDV	Heavy Duty Vehicle
EU	European Union
CO_2	Carbon Dioxide
SMR	Steam Methane Reforming
PEM	Proton Exchange Membrane
TCO	Total Cost of Ownership
CNG	Compressed Natural Gas
LNG	Liquefied Natural Gas
CBG	Compressed Biogas
LBG	Liquefied Biogas
GHG	Greenhouse Gas
SOEC	Solid Oxide Electrolysis Cell
CCS	Carbon Capture and Storage

CAPEX	Capital Expenditure
OPEX	Operating Expenditure
IRR	Internal Rate of Return
FCEV	Fuel-Cell Electric Vehicle
SWOT	Strengths-Weaknesses-Opportunities-Threats
CH_4	Methane
H_2S	Hydrogen Sulfide
UN	United Nations
IEA	International Energy Agency
HTE	High Temperature Electrolysis
PSA	Pressure Swing Adsorption

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Grammarly has been used to check the grammar of this thesis.

1 Introduction

Heavy-duty vehicles (HDVs) are an important part of global trade, accounting for approximately 75% of inland freight transport in the European Union (ACEA, 2024). However, the excessive use of diesel has caused severe environmental pollution, particularly global warming or climate change, caused by greenhouse gas emissions (Chhugani & Rahmani, 2025). These emissions highlight the urgent need for alternative fuels to reduce the environmental impact of HDVs.

HDVs account for approximately a quarter of European Union (EU) road transport carbon dioxide emissions (Chhugani & Rahmani, 2025). This large share is due to heavy-duty vehicles' high fuel consumption and large engine size. In response, governments and organizations worldwide are pursuing net-zero emission strategies, including replacing fossil fuels with alternative energy sources and aiming to reduce greenhouse gas emissions by 487.7 million tons by 2030 (IEA, 2025). In addition, the projected demand for freight transportation is expected to grow by 100 % in 2050 (United Nations, n.d.). Considering the urgency of tackling GHG emissions, many plans have been underway in recent years to address this problem. In 2019, the United Nations (UN) initiated a climate action summit focusing on energy, industry, transport, nature-based solutions, urban planning, resilience, and adaptation (United Nations, n.d.). Around 100 organizations came together to switch to zero emissions from all forms of transportation. UN's landmark global decarbonization strategy aims to achieve net-zero GHG emissions from inland transportation by 2050 (IEA, n.d.). Currently, the policy of the International Energy Agency is to decarbonize through electrification, but this approach faces many challenges and resistance, which may necessitate extensive upgrades to grid infrastructure. It also requires improved batteries to cope with the greater weight and range of trucks. The costs and lead times for these developments could hinder progress (IEA, n.d.). To solve these challenges, biogas and hydrogen are two promising alternative energy sources.

Hydrogen is produced from renewable sources (Hermesmann & Müller, 2022), with zero emissions and high energy efficiency. Biogas, which comes from organic waste, is a renewable, low-carbon alternative that is in line with circular economy principles (Godoy et al., 2024). Alongside the push for more sustainable energy solutions, safety considerations are pivotal for the large-scale adoption of alternative fuels in HDVs. Whether dealing with high-pressure hydrogen systems or biogas with potentially corrosive impurities, each fuel type presents distinct risks that must be thoroughly considered in vehicle design and the construction of refuelling stations (Basma et al., 2022). Failure to implement robust safety measures could undermine public confidence and negate the cost benefits gained from cleaner and more efficient fuels (Yang et al., 2021). Therefore, besides examining the techno-economic aspects of hydrogen and biogas, this thesis also highlights fundamental safety factors that influence operational feasibility.

Hydrogen and biogas are alternatives to diesel for HDVs, but both still face economic and technical uncertainties. Selecting the optimal fuel type regarding total cost of ownership, operational feasibility, and sustainability for HDVs is a complex decision beyond comparing fuel prices or emission levels (Lee et al., 2021). It requires a holistic approach that accounts for all relevant economic and operational factors throughout a vehicle’s lifecycle. This is where the Total Cost of Ownership (TCO) analysis becomes crucial. TCO provides a comprehensive economic evaluation by integrating initial investment costs, fuel expenditures, infrastructure expenses, maintenance, and residual values into a unified calculation (Basma & Rodríguez, 2023). By performing a TCO analysis, decision-makers can effectively quantify and compare the economic viability of different fuel types, considering both immediate and long-term financial impacts. This approach allows stakeholders to identify the most cost-effective, sustainable, and operationally feasible fuel option for heavy-duty transport (Lee et al., 2021). Moreover, safety cannot be ignored, just like electric vehicles, which need reassurance of safety from the outset. Otherwise, consumers will lose faith in them, insurance costs will increase, and there will be incalculable consequences for commercialization (FNR, n.d.). The research identifies the most cost-effective fuel from the alternative fuel types considered in this study for HDVs over a five-year study period.

2 Literature review

Converting HDVs to alternative fuels has become an important part of reaching global decarbonization targets. Hydrogen and biogas have more advantages than diesel regarding environmental and operational feasibility (Godoy et al., 2024) (Chhugani & Rahmani, 2025). This section will explore their features, working principles, and challenges.

2.1 Hydrogen-powered heavy-duty vehicles

Hydrogen has gained increasing attention as a clean and efficient alternative fuel for decarbonizing the HDV sector. Its high energy content per unit mass, rapid refuelling capability, and compatibility with fuel cell technologies make it a promising solution for reducing greenhouse gas emissions in long-haul transport. However, the environmental and economic performance of hydrogen-powered HDVs greatly depends on how the hydrogen is produced, stored, and integrated into transport systems. The following sections explore these key technical aspects in more detail.

2.1.1 Hydrogen production methods

Two primary methods are used to produce hydrogen: steam methane reforming (SMR) of natural gas and electrolysis of water.

Steam methane reforming is the most established and popular method of producing hydrogen, particularly due to its compatibility with large-scale centralized production, which allows for economies of scale and reduces production costs (Mehmeti et al., 2018). Compared to commercially existing production techniques, this technology route is essential for producing hydrogen soon and provides a practical, cost-effective, and environmentally benign alternative. The two steps in the SMR process are as follows:

$$\mathrm{CH_4 + H_2O \leftrightarrows CO + 3H_2} \tag{1}$$

$$\mathrm{CO + H_2O \leftrightarrows CO_2 + H_2} \tag{2}$$

SMR uses natural gas as the most common feedstock. Natural gas consists mainly of methane (CH_4) mixed with some heavier hydrocarbons and CO_2. Applying high-temperature steam to the CH_4 creates carbon monoxide, syngas mixtures, a combination of hydrogen and carbon monoxide, steam, and electric power for customer use (Mehmeti et al., 2018).

Another method for producing high-quality hydrogen is electrolysis, which converts water electrochemically to generate hydrogen and oxygen.

$$2H_2O + \text{electrical energy} \rightarrow O_2 + H_2 \tag{3}$$

An electrolyte separates the anode and cathode of an electrolyser, where the previously mentioned process occurs. Nowadays, the two primary industrial electrolysis technologies that produce hydrogen are high temperature (650–850°C) electrolysis based on solid oxide electrolysis cells (SOEC) and low temperature (70–90°C), which includes alkaline electrolysers and proton exchange membranes (PEM) (Carmo et al., 2013). An environmentally friendly method of producing hydrogen combines electrolysers with solar and wind energy.

By employing SOEC to produce hydrogen from high-temperature electrolysis (HTE), a larger percentage of the energy needed may be supplied as heat instead of electricity, increasing the system's overall energy efficiency (Harvego, O'Brien and McKellar, 2012). Conversely, PEM's primary benefits are improved coupling with dynamic and intermittent systems, more flexibility, and quicker cold start. Both power and deionized water are necessary inputs for the procedure. The electrolysis procedure typically uses highly pure water. (Mehmeti et al., 2018).

2.1.2 Different types of hydrogen

Grey hydrogen is the most commonly produced form of hydrogen today and is typically derived from natural gas through steam methane reforming (SMR). In this process, methane reacts with steam under high temperatures, generating hydrogen and carbon dioxide. However, no carbon capture mechanism is involved, so all the CO_2 produced is released directly into the atmosphere (Hermesmann & Müller, 2022). This results in a high carbon footprint despite relatively low production costs. Grey hydrogen is widely used due to its economic efficiency, but is unsustainable in the long term due to environmental concerns. The production process is presented in Figure 1.

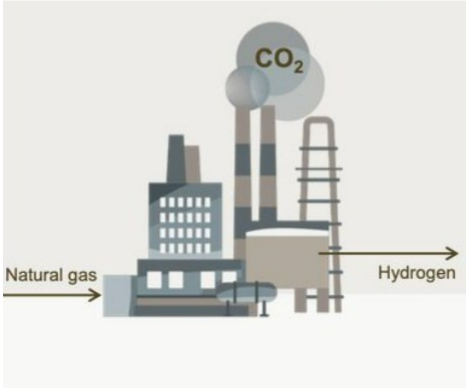

Figure 1. Grey hydrogen (Energy Tracker Asia, n.d.).

Blue hydrogen follows a similar production pathway to grey hydrogen, using SMR as its base method. The key difference is the inclusion of carbon capture and storage (CCS) technologies, which aim to trap a significant portion of the CO_2 emissions before they are released (Newborough & Cooley, 2020). While this approach reduces greenhouse gas emissions, it is not entirely emission-free. CCS systems often fail to capture 100% of the carbon, and their deployment is energy-intensive and costly (Hermesmann & Müller, 2022). Blue hydrogen is a transitional solution between grey and green hydrogen, especially where existing SMR infrastructure exists. The production process is presented in Figure 2.

Figure 2.Blue hydrogen (Energy Tracker Asia, n.d.).

Green hydrogen is produced through electrolysis, which splits water molecules into hydrogen and oxygen using electricity from renewable sources such as wind or solar power. Green hydrogen has zero lifecycle emissions since no fossil fuels are involved, and the electricity is carbon-free (Harvego, O'Brien and McKellar, 2012), and emissions only remain from the infrastructure phases. This makes it the most environmentally sustainable option. However, its widespread adoption is currently limited by high production costs, the need for vast renewable energy capacity, and expensive electrolyzer technology (Mehmeti et al., 2018). Nonetheless, green hydrogen is central to long-term decarbonization goals in the transport and energy sectors (Newborough & Cooley, 2020). The production process is presented in Figure 3.

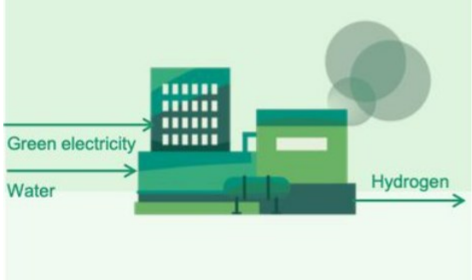

Figure 3. Green hydrogen (Energy Tracker Asia, n.d.).

Despite their shared chemical identity of hydrogen, grey, blue, and green hydrogen each present vastly different carbon footprints and production costs. Grey hydrogen’s well-established SMR pathway makes it abundant yet environmentally burdensome, while blue hydrogen attempts to mitigate emissions but is contingent on efficient carbon capture and storage (Chhugani & Rahmani, 2025). Meanwhile, green hydrogen stands out as the most sustainable option thanks to renewable electrolysis, although it remains cost-intensive and relies on large-scale renewable energy integration. As governments and industry stakeholders push toward deep decarbonization, green hydrogen is increasingly viewed as the ultimate goal, subject to ongoing technological advancements, policy incentives, and the scaling-up of electrolyzer capacity (Hermesmann & Müller, 2022).

2.1.3 High-pressure hydrogen storage

High-pressure storage is a standard method to store hydrogen by compressing it into tanks, significantly increasing its volumetric energy density. Currently, the prevalent storage pressure levels used in transportation are 350 and 700 bar (Li et al., 2019). The volumetric energy density of hydrogen at 350 bar is approximately 26.1 kg/m^3, while at 700 bar, it increases to around 42 kg/m^3 (Anastasiadis et al., 2023). Consequently, 700-bar storage systems can store more energy within the same volume as 350 bar systems (Li et al., 2019), making them particularly suitable for long-distance transportation applications where vehicle range is critical.

However, the increased pressure at 700 bar demands more advanced materials and tank designs to ensure durability and safety. Moreover, compressing hydrogen to higher pressures also requires more energy, thus potentially reducing overall system efficiency and increasing operational costs (Zheng et al., 2013) (de Miguel et al., 2015). The weight of the storage tanks at higher pressures may further impact vehicle performance and payload capacity.

Therefore, selecting the optimal hydrogen storage pressure from a techno-economic perspective involves balancing factors such as volumetric energy density, tank weight, efficiency, and safety considerations. Despite these challenges, the higher energy density of 700 bar storage typically outweighs these drawbacks for HDVs intended for extended-range and long-haul operations.

2.2 Biogas-powered heavy-duty vehicles

Biogas consists of methane, produced through anaerobic digestion. The methane content in biogas typically ranges from 45 % to 75 %, depending on the type of feedstock and the production technique. At the same time, the remaining composition primarily includes CO_2 and traces of other gases such as ammonia, carbon monoxide, H_2S, and nitrogen (Godoy et al., 2024). During anaerobic digestion, microorganisms break down organic materials in agricultural waste, food waste, or sewage under anaerobic conditions. After removing impurities such as CO2, N2, and water, biomethane containing more than 96 % CH_4 can be obtained (Godoy et al., 2024). After compression or liquefaction, biomethane is utilized as a fuel.

The energy density of liquefied CH_4 is around 55.7 MJ/kg (Dorin, Demmin and Gabriel, 1987), and it is about 600 times higher than that of gaseous CH_4 at atmospheric pressure and 2.5 times higher than that of CH_4 at 250 bar (Benjaminsson and Nilsson, 2009). Due to the relatively high energy density, lower sulfide content, and lower life cycle GHG emissions compared to diesel or heavy fuel oil, liquid natural gas (LNG) or liquid biogas (LBG) have emerged as alternative fuels for heavy road and sea transport (Gustafsson et al., 2020).

Each stage incurs costs and has associated environmental impacts, such as methane leakages, that could reduce net GHG benefits if not well controlled. The following subsections compare the technical and economic aspects of CBG and LBG, highlighting their respective advantages and challenges in HDV applications.

2.2.1 Compressed biogas

Compressed biogas (CBG) is biomethane compressed to around 250 bars (Deval, Mamta and Sunil, 2023) in shorter-range vehicles, making it more suitable for its requirements. This approach leverages existing natural gas infrastructure, as CBG can often be distributed via pipelines or trucked in high-pressure cylinders to refuelling stations.

Figure 4 illustrates the detailed production and application process of CBG. Initially, organic feedstock such as agricultural waste, sewage sludge, or food waste undergoes anaerobic digestion, producing raw biogas. This raw biogas, mainly composed of methane and carbon dioxide, is upgraded through purification techniques to remove CO_2, water vapor, and impurities like H_2S. The resulting biomethane is then compressed to high pressures for storage and transported to fuelling stations for vehicle fuel.

From an economic perspective, CBG typically involves lower processing costs than liquefaction, but distribution may be limited by pipeline availability or the need for specialized high-pressure trailers. Environmentally, CBG offers significant life-cycle GHG reductions compared to diesel when feedstocks are sourced sustainably and methane slip is minimized (Yadav et al., 2024). However, cost-effectiveness depends on the proximity of feedstock supplies and the scale of anaerobic digestion and upgrading plants (Deval, Mamta and Sunil, 2023). More extensive centralized facilities often benefit from economies of scale, reducing the levelized cost of the biomethane produced.

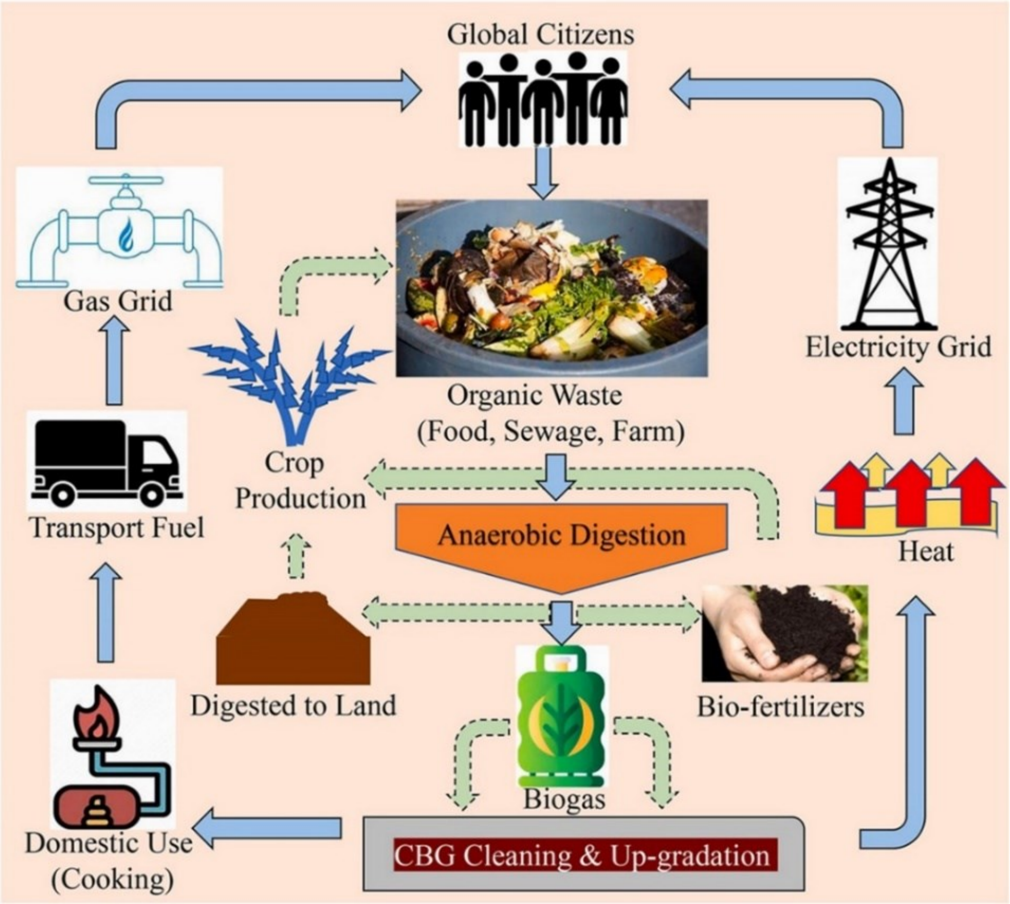

Figure 4. Compressed biogas process (Deval, Mamta and Sunil, 2023).

2.2.2 Liquefied biogas

Liquefied Biogas is produced by cooling biomethane to - 162 °C, transforming it into a liquid state (Benjaminsson and Nilsson, 2009). Liquefaction can offer significant financial and environmental benefits for long-distance distribution, primarily because LBG has a much higher energy density than compressed biogas, enabling more fuel to be transported in a smaller volume. This reduces transportation costs and emissions per unit of energy delivered, particularly in regions lacking pipeline infrastructure (Edwards et al., 2014). Liquefaction can significantly increase the feasible distribution range for enhanced biogas in countries like Sweden, which lack national gas infrastructure. Otherwise, because propane additive may be eliminated, distribution via pipeline or grid would be better. LBG has a higher energy density and allows longer driving ranges, making it suitable for long-haul HDVs (Gustafsson et al., 2020). However, the adoption of LBG requires specialized cryogenic storage and distribution infrastructure.

Figure 5 shows the process of producing liquefied biomethane (LBG). Raw biogas from anaerobic digestion is first cleaned to remove impurities like water, H_2S, and oxygen. It is then upgraded to over 95% methane using absorption, pressure swing adsorption (PSA), cryogenic separation, and membrane systems. Finally, it is liquefied through mixed refrigerant or nitrogen expander processes for long-distance heavy-duty transport.

The main technical challenge lies in maintaining cryogenic temperatures to prevent fuel loss through boil-off, requiring robust insulation and continuous pressure monitoring (Qudratullah et al., 2020). Given the energy-intensive liquefaction process, LBG production plants also entail higher capital and operational expenditures compared to compression facilities (IRENA, 2018). Nonetheless, LBG can reduce refuelling frequency for fleets covering extensive routes and potentially lower overall logistics costs, provided there is sufficient demand density to justify the investment in liquefaction infrastructure (Sia Partners, 2021).

Regarding environmental impact, LBG shows similar or even greater GHG reduction potential than CBG, assuming low methane leakage and responsible feedstock sourcing (Godoy et al., 2024). While its environmental benefits are clear, the economic feasibility of LBG production also depends on factors such as plant scale and geographic location. Liquefaction plants typically require large volumes of biomethane to be economically viable, favoring regions with abundant feedstock or existing gas grid connections. Similar to CBG, government subsidies, carbon credits, or other policy incentives often play a decisive role in determining overall feasibility.

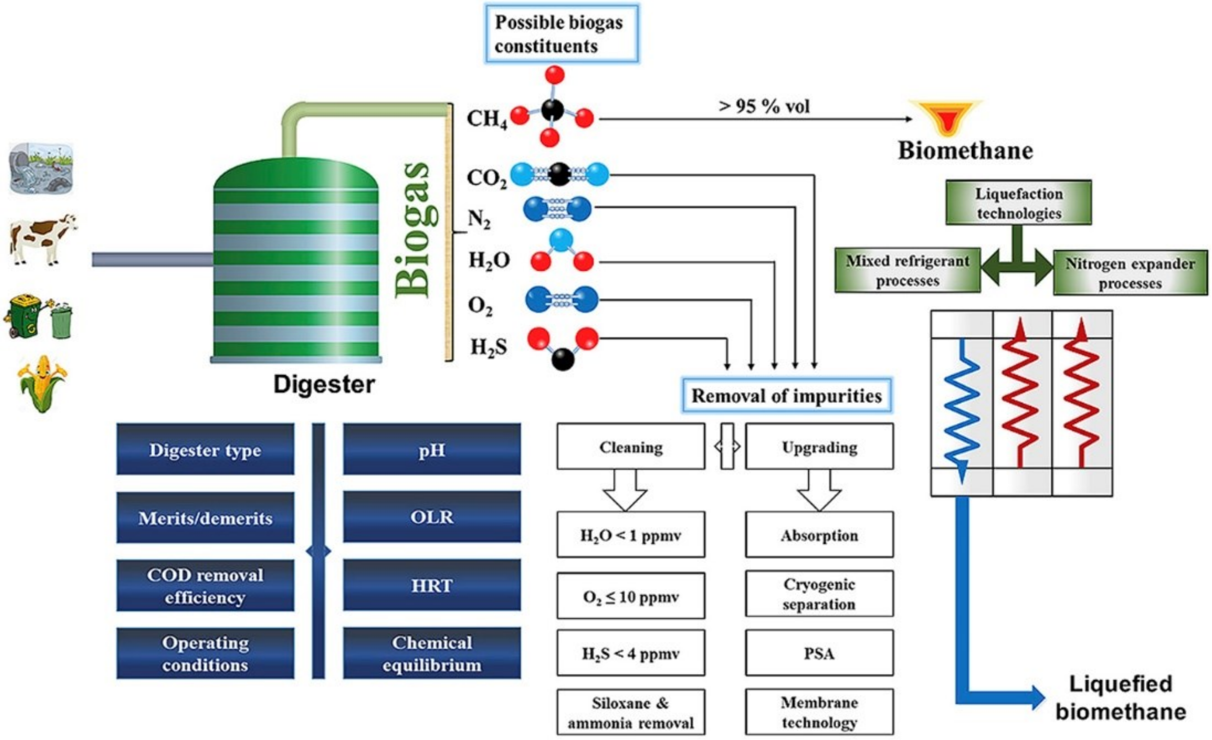

Figure 5. Liquefied biogas process (Qudratullah et al., 2020).

2.3 SWOT analysis

This section performs a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to comprehensively understand the potential and limitations of hydrogen and biogas for HDVs. The analysis is based on an extensive review of literature and technical reports, supplemented by data and insights presented in previous sections of this thesis. By examining each fuel's strengths, weaknesses, opportunities, and threats, decision-makers can identify critical factors that affect technical feasibility, economic viability, and market adoption (Benzaghta et al., 2021). This analysis aims to aid stakeholders in strategic planning and inform future directions for sustainable transport solutions. The detailed SWOT comparison of hydrogen and biogas is presented in Table 1.

Table 1. SWOT analysis.

Aspect	Hydrogen	Biogas
Strengths	Zero tailpipe emissions	Renewable fuel from waste
	High energy density, fast refuelling	Lower net carbon emissions
	Growing policy incentives	Infrastructure is partly compatible with natural gas
Weaknesses	The current reliance on gray and blue H_2	Feedstock availability varies regionally
	Limited refuelling infrastructure	Lower energy density (CBG)
	High vehicle purchase cost	LBG storage cost
Opportunities	Technology cost reduction via scale	Circular economy benefits
	Potential for synergy between green hydrogen and renewables	Expanding feedstock processing technologies
		Policy incentives for renewable fuels
Threats	Delays in building hydrogen corridors	Competition for biomass
	Competition from other electrification routes	Infrastructure investment requirements
	Volatile electricity prices	

The SWOT analysis shows that hydrogen has substantial environmental benefits but faces high costs and infrastructure limitations. Biogas, while more cost-effective and compatible with existing systems, is limited by feedstock availability. Both fuels present opportunities through policy support and technological development, but each also faces challenges to adoption. This comparison helps clarify the trade-offs in choosing sustainable fuels for HDVs.

2.4 Safety

Although this thesis primarily focuses on economic feasibility and technical performance, ensuring the safe handling, storage, and transport of different fuels is an integral part of their overall viability (Casson Moreno et al., 2017; Yang et al., 2021). In heavy-duty transport operations, any lack of safety can lead to severe incidents, increased insurance costs, and reduced public acceptance, negating cleaner fuels' benefits. Below is a concise overview of the key safety aspects of hydrogen and biogas.

2.4.1 Hydrogen safety

Hydrogen energy and fuel cells have the potential to significantly reduce energy and pollution issues related to traffic, particularly in sectors such as power generation, transportation, and industrial applications (Chen et al., 2020). However, due to the intrinsic properties of hydrogen, it is challenging to ensure safety throughout production, storage, transit, and usage (Moradi & Groth, 2019; Najjar, 2013). Low molar mass indicates low gas density, absence of color, and the possibility of flaming, which makes identification more difficult, and the potential for burning when air is combined with a hydrogen volume fraction of only 4% are characteristics of hydrogen. Leaks, ignition, and potential explosions can be prevented by manipulating hydrogen under safe, dependable settings that limit equipment interaction with H_2 (Yang et al., 2021). In addition, strict protocols must be followed during refuelling to minimize ignition risks and pressure-related hazards.

2.4.2 Biogas safety

The process of producing biogas involves complex biological interactions that pose several risks. The primary source of inherent risk in production facilities is biogas, a mixture of carbon dioxide (15–60%) and methane (40–75%) (FNR, n.d.). Consequently, there is a chance that an explosion could occur at a methane volume of between 5 and 15 % in the atmosphere (Schroeder et al., 2013). H_2S, a by-product of the anaerobic digestion of organic material, is particularly concerning because of its high toxicity, short-term exposure limit of 10 ppm, and corrosiveness. Raw biogas can contain H_2S concentrations between 50 and 20,000 ppm (Casson Moreno et al., 2017). However, before being used as vehicle fuel, biogas is typically upgraded to remove H_2S and other impurities to meet safety and performance standards.

3 Methodology

This section focuses on the methodological framework for evaluating the techno-economic feasibility of hydrogen and biogas-powered HDVs. It outlines the calculation processes, assumptions, and analytical tools that compare the alternative fuels with conventional diesel. The methodology comprehensively analyzes fuel consumption, infrastructure requirements, and TCO per kilometre. The chapter also includes sensitivity analyses to assess the impact of key variables. Figure 6 illustrates the route used in this study to calculate all the associated costs.

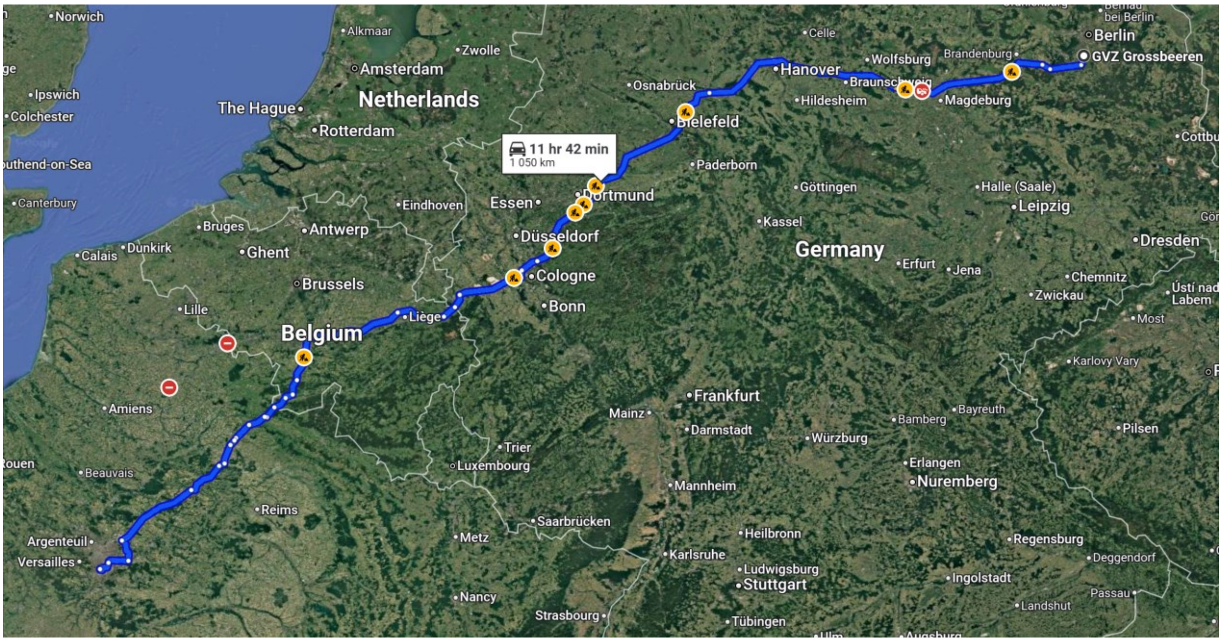

Figure 6. Route under study from GVZ Grossbeeren, Hauptstraße 2, 14979 Großbeeren, Germany to 1 Rue de la Tour, 94152 Rungis, France.

3.1 Calculation formula and data explanation

This study calculates several key parameters, including annual fuel consumption, fuel prices, road tolls, labor costs, vehicle prices, refuelling stations, and the TCO per kilometre, to evaluate the cost-effectiveness of hydrogen and biogas-powered HDVs. These calculations form the basis for comparing the economic performance of different fuel types over a five-year operational period.

3.1.1 Basic data

According to the EU, road transport workers are required to drive a maximum of 9 hours per day and an average of 48 hours per week (European Union, n.d.). The route under the study will take around 11.5 hours, assuming the round trip can be completed in three days. Due to the uncertainty surrounding government support for hydrogen, such as potential price changes or even withdrawal of investment as seen in Japan (Modiauto, n.d.), this thesis limits the analysis to a five-year study period.

Truck drivers do not drive continuously throughout the year due to legal restrictions, weekly rest time, and vacations. These legal restrictions lead to an assumption that there are 234 operational days in one year. The data for the case route under study is presented in Table 2

Table 2. Basic data

Parameter	Value
Departure and destination	Berlin to Paris
Route length	1,050 km (one-way)
Route length	2100 km (round-trip)
Vehicles	1
Operational days	234 days/year
Study period	5 years

The total mileage covered by the HDVs in the study is calculated using the following formula:

$$D_{\text{total}} = D_{\text{round}} \times \frac{T_{\text{operation}}}{3} \tag{4}$$

Where D_{total} is the total mileage [km], D_{round} is the round-trip distance [km], $T_{\text{operation}}$ is Operational Days

3.1.2 Fuel consumption rate

For this study, the Berlin-to-Paris route shown in Figure 6 is analyzed without considering the effects of weather or topography. These factors are excluded as their impact on fuel consumption requires highly specific data, which is beyond the scope of this analysis. Instead, the average fuel consumption rates provided in the literature are used to calculate fuel usage for each vehicle type. These consumption rates represent typical values under standard operating conditions, ensuring a fair comparison.

It is also assumed that all vehicles carry the same payload, 19 tons, ensuring consistency in the analysis. Despite differences in fuel storage systems, the payload remains unchanged, as modern vehicle designs mitigate storage-related weight penalties through optimized chassis and tank configurations (Zacharia et al., 2021). This assumption aligns with the practical requirements of long-haul freight transport, where maintaining payload capacity is critical for operational efficiency and cost-effectiveness.

Current hydrogen HDVs use about 9 kg of hydrogen every 100 km (Basma, 2022). The data did not show that the hydrogen is 700 or 350 bar. However, the specific HDV XCIENT fuel cell tractor allows 400 km with 31 kg of 350 bar hydrogen, another vehicle allows 725 km with 68.6 kg of 700 bar hydrogen (Hyundai, n.d.), and the MAN hTGX hydrogen-powered HDVs can travel 600 km with 56.8 kg of 700 bar hydrogen (Yiche, n.d.). Since fuel consumption varies with payload, this study assumes a uniform payload of 19 tons across all HDVs to minimize variability in the analysis. Several things greatly influence this fuel usage. Among these are the vehicle's weight and load distribution, which have a direct impact on rolling resistance, aerodynamic design, where inadequate streamlining can increase drag, driving habits, and operating conditions, especially frequent braking, acceleration, challenging road conditions and the terrain and road quality, where poor surfaces and steep gradients lead to higher fuel consumption and environmental factors, like extremely high or low temperatures, which can lower fuel cell efficiency (Zacharia et al., 2021). Using actual data, Table 3 will examine fuel consumption for different vehicle kinds and scenarios.

Table 3. Fuel consumption rate

Fuel type	Fuel consumption rates	Fuel consumption rates (MJ/km)
Hydrogen (700 bar)	9.5 kg/100 km	11.40
Hydrogen (350 bar)	7.75 kg/100 km	9.30
Biogas (Liu et al., 2022)	57 m³/100 km	12.54
Diesel (Song et al., 2017)	43 L/100 km	15.91

In order to better compare the energy of each energy source, the units are converted to MJ/km, which is presented in Figure 7.

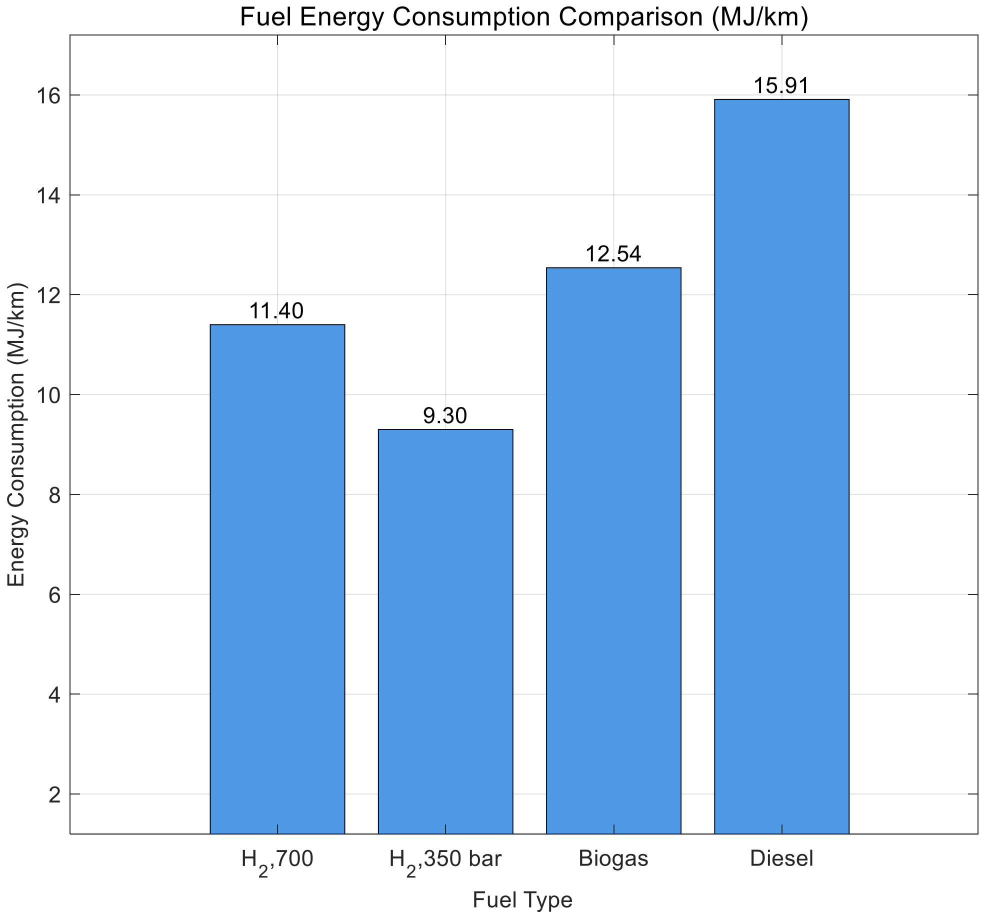

Figure 7. Fuel energy consumption comparison.

For each fuel type, the annual total fuel consumption is:

$$F_{\text{total}} = \frac{D_{\text{total}} \times F_{\text{rate}}}{100} \tag{5}$$

Where F_{total} is total fuel consumption [kg, m³, L], D_{total} total distance traveled [km], F_{rate} fuel consumption rate [kg/100 km, m³/100 km, L/100 km]

3.1.3 Fuel price

In Europe’s hydrogen market, the final retail price paid by end users is mainly driven by upstream production costs, especially electricity, and equipment for green hydrogen, compression, and storage requirements, which increase with higher pressures, and downstream transportation and distribution expenses, including infrastructure for refuelling stations (El-Taweel, Khani and Farag, 2019). Policy instruments such as carbon taxes and subsidies also significantly affect pricing. Consequently, hydrogen compressed at 350 bar typically costs around €9 to €15 per kilogram, while 700 bar hydrogen, requiring more advanced compression and storage technology, generally ranges from €12 to €18 per kilogram (H_2. LIVE. 2021). This study focuses on a transport route from Germany to France, among the countries with relatively high hydrogen prices in Europe.

Production costs depend on feedstock availability, technology for upgrading and liquefaction/compression, and infrastructure requirements. Government incentives and carbon taxation also notably affect final retail prices. In practice, LBG’s higher energy density favours HDV over longer distances, while CBG is more common for shorter routes or local networks. Recent station data illustrate LBG retail prices around 30.22 SEK/kg (≈2.67 EUR/kg, 1.90 EUR/m³) and CBG at roughly 30.12 SEK/kg (≈2.67 EUR/kg, 1.91 EUR/m³) in Sweden or 1.99 EUR/kg (≈1.42 EUR/m³) in Finland (Gasum, n.d.). Fuel prices are introduced in Table 4.

Because of the different government policies, fuel production, and energy storage, the price of each fuel will change every year, so based on the information, the hydrogen fuel price will decrease by 10 % annually due to advancements in green hydrogen production technology (Basma et al., 2022) and the support of government. Furthermore, for biogas, economic analysis of these scenarios showed that projects are profitable with high internal rate of return (IRR) values (between 15 and 40 %) and low payback periods (between 3 and 7 years) only if biomethane is sold for the price of 60 €/MWh (it corresponds to the price of €0.55/m³) or above (Robert et al., 2020). So, in the next five years, the biogas price is expected to decrease by 5% annually as biogas production technologies improve and the availability of feedstocks increases. The diesel price trend in 2025-2030 will largely depend on the dynamics of the crude oil market, policy adjustments, and progress in the energy transition. The oil price, which has shown a deep decay in recent years, will gradually reach around $70 per barrel ($41 per barrel in 1993 USD) in the next five years (Hossein et al., 2021), so the diesel price is expected to increase by 3 % annually.

Table 4. Fuel price

Fuel type	Fuel price
Green hydrogen (350 bar) (H_2. LIVE. 2021)	€13/kg
Green hydrogen (700 bar) (H_2. LIVE. 2021)	€16/kg
Biogas (CBG) (Gasum, n.d.)	€1.5/m³
Biogas (LBG) (Gasum, n.d.)	€1.9/m³
Diesel (Cargopedia, n.d.)	€1.5/L

Total fuel cost in the five-year study period:

$$C_{\text{fuel,t}} = F_{\text{total}} \times P_{\text{fuel}} \times (1 + r_{\text{fuel}})^{t-1} \tag{6}$$

Where P_{fuel} is the initial fuel price [€/kg, €/L, or €/m³], r_{fuel} is the annual fuel price change, and *t* is the year.

3.1.4 Refuelling station

Because the total one-way distance between Berlin and Paris is 1050 km, the vehicle range affects the number of refueling stations required for the route under study. As diesel and CBG-powered trucks can each cover over 1500 km on a full tank, given that LBG-powered trucks can travel over 1500 km on a full tank, a practical solution is to place a refuelling station at the destination in France, where vehicles can refuel before making the return trip. However, the CBG only has a 600 km range, so two refuelling stations ensure that vehicles can complete a 1050 km trip and handle the return leg without risking fuel depletion. A practical solution is to place one refuelling station roughly at the midpoint, around 550 km from the origin, or near a central logistics hub along the route. Another station can be co-located with the LBG facility at the destination in France. This setup is generally considered the most convenient and cost-effective, enabling vehicles to refuel once in each direction without significant detours.

In contrast, hydrogen trucks with a 700 km range need two refuelling stations along the same route. However, hydrogen trucks with a maximum driving range of 400 km require three refuelling stations along the route. A strategy is to space the stations at about 350–400 km intervals so vehicles can travel between stations without running out of fuel. For example, one station could be located about 350 km from the starting point, another around 700 km, and the last refuelling station located at the destination in France, such as a biogas refuelling station. It provides sufficient redundancy should unexpected factors (e.g., traffic or detours) increase hydrogen consumption on the route. Finally, the expected refuelling stations along this road are in Figure 8.

The number of refueling stations required is due to the refuelling frequency of each type of vehicle over 1050 km one way.

$$N_{\text{station}} = [\frac{L}{R_{\text{vehicle}}}] \tag{7}$$

Where $N_{\text{station}}$is the number of refuelling stations, L is the length of the route [km], R_{vehicle} is the vehicle range [km].

The annual labor and material maintenance cost for hydrogen refuelling stations is estimated at 4.3 % of capital expenditures (CAPEX) (Fuel Cells and Hydrogen 2 Joint Undertaking, 2017). In contrast, maintenance for biogas refuelling stations is estimated at 10-15 % of total operational costs (Business Plan Templates, n.d.). Diesel infrastructure costs are not included, as diesel refuelling networks are already mature and widely available. The refuelling station construction and maintenance cost is presented in Table 5.

Table 5. Refuelling station construction and maintenance costs

Refuelling station fuel type	Refuelling station or maintenance cost
Hydrogen station costs (350 and 700 bar) (U.S. Department of Energy, 2021)	€1,800,000/station
Hydrogen station annual maintenance Costs (350 and 700 bar)	€77,400/year
Biogas station construction costs (CBG and LBG) (Sia Partners, 2021)	€1,300,000/station
Biogas station annual maintenance costs (CBG and LBG)	€130,000/year
Diesel annual maintenance costs (Smajla, Karasalihović Sedlar, Drljača, & Jukić, 2019)	€9570/year

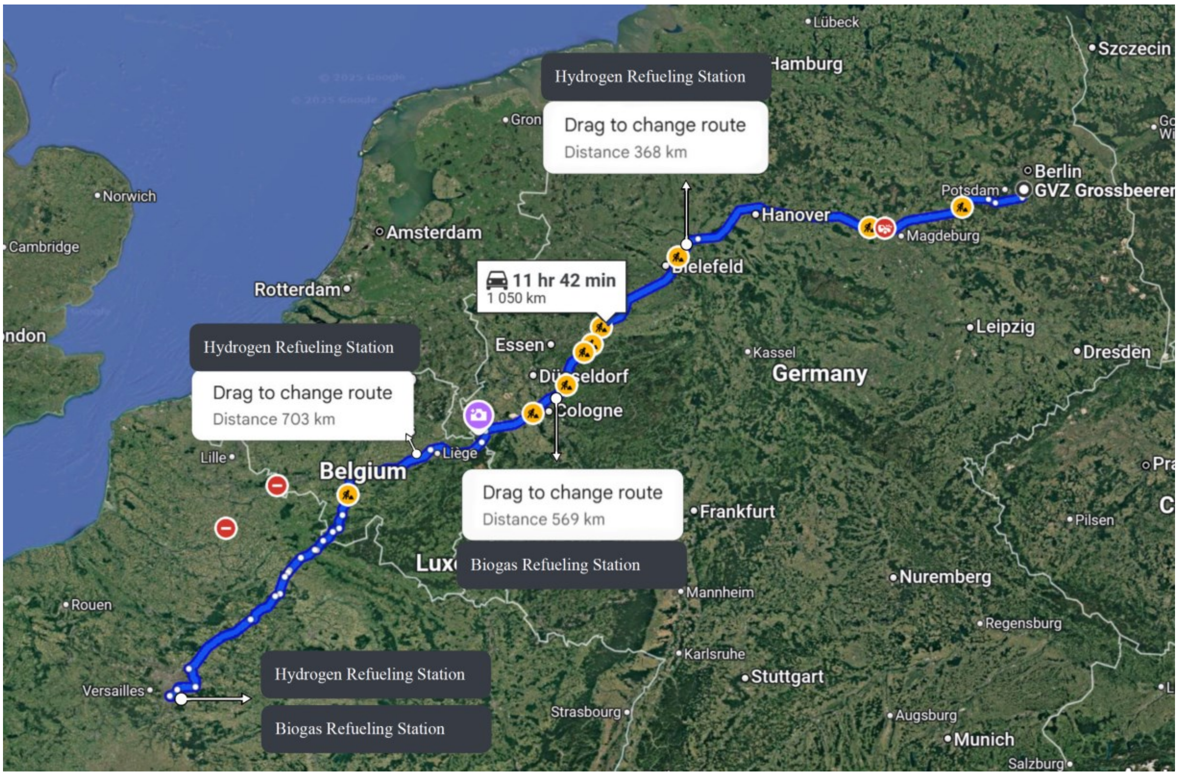

Figure 8. Refuelling station on the road.

3.1.5 Truck road tolls

Furthermore, truck road tolls must be included, as these tolls significantly contribute to operational expenses over long distances. Monitoring toll policy developments remains crucial for accurate cost assessments, especially since this route under study passes only through Germany, Belgium, and France. It considers the tolls of these three countries and averages the prices among them due to the differing rates in each country.

Table 6. Truck road tolls (Basma & Rodríguez, 2023)

Fuel type	Truck road tolls
Green hydrogen vehicle (350 bar)	0.185€/km
Green hydrogen vehicle (700 bar)	0.2€/km
Biogas vehicle (CBG)	0.185€/km
Biogas vehicle (LBG)	0.207€/km
Diesel	0.207€/km

The total truck road toll in the study is calculated using the following formula:

$$C_{\text{toll,total}} = D_{\text{total}} \times C_{\text{toll}} \tag{8}$$

Where $C_{\text{toll,total}}$ is total truck road [€], C_{toll} is truck road tolls [€/km].

3.1.6 Labor cost

Not to be overlooked in the transportation process are the drivers, whose labor costs were also included in the five-year study. From data in the study (Basma & Rodríguez, 2023), the labor cost per hour in Europe is 25.56€. This route under the study will take three days for a round trip, each lasting 9 hours. The total labor cost is calculated using the following formula:

$$C_{\text{labor}} = 25.56 \times 9 \times T_{\text{operation}} \tag{9}$$

Where C_{labor} is total labor cost [€].

3.1.7 Vehicle range and vehicle price

The operational range of a vehicle directly impacts the number of refuelling stops required during a journey, which in turn influences route planning, travel time, and infrastructure investment. Table 7 presents the estimated driving ranges of HDVs powered by various fuels.

Table 7. Vehicle range

Vehicle fuel type	Vehicle range
Green hydrogen (350 bar) (Hyundai, n.d.)	400 km
Green hydrogen (700 bar) (Hyundai, n.d.)	725 km
Biogas (CBG) (Gasum, n.d.)	600 km
Biogas (LBG) (Gasum, n.d.)	1,600 km
Diesel	1,700 km

In addition to range, the purchase price of vehicles significantly affects the TCO and the overall economic feasibility of adopting a particular fuel type. Table 8 lists the approximate purchase prices for each vehicle type based on current market estimates.

Table 8. Vehicle price (Basma & Rodríguez, 2023)

Fuel type of vehicle price	Vehicle price
Hydrogen (350 bar)	250,000 €
Hydrogen (700 bar)	320,000 €
Biogas (CBG)	160,000 €
Biogas (LBG)	190,000 €
Diesel	180,000 €

3.1.8 Total cost of ownership

The TCO framework evaluates the overall costs of operating hydrogen, biogas, and diesel-powered HDVs over a five-year study period. The TCO accounts for CAPEX and operational expenditures (OPEX), providing a comprehensive view of each fuel type's financial implications.

TCO Formula:

$$TCO = C_{\mathrm{capex}} + \sum_{t=1}^{T} \frac{C_{\mathrm{opex,t}}}{(1+r)^t} - \frac{S_{\mathrm{T}}}{(1+r)^T} \tag{10}$$

C_{capex} are initial capital costs [€], $C_{\mathrm{opex,t}}$is operating costs for year t (fuel, maintenance, etc.) [€], r is discount rate, assume to be 5 %, T is study period [year]. S_{T} is salvage value at year [€].

TCO per kilometer:

$$TCO_{\mathrm{km}} = \frac{C_{\mathrm{capex}} + \sum_{t=1}^{T} \frac{C_{\mathrm{opex,t}}}{(1+r)^t} - \frac{S_{\mathrm{T}}}{(1+r)^T}}{\sum_{t=1}^{T} D_{\mathrm{t}}} \tag{11}$$

Where D_{t} [km] is the mileage traveled in year t

Also, each truck is assumed to have a total technical lifetime of 10 years, but the economic analysis focuses on the first 5 years. At the end of the 5 years, the vehicle is assumed to decrease by 50 % of its original purchase value. To accurately reflect this residual asset value, the TCO model deducts the salvage value at the end of the study period.

Salvage value:

$$S_{\mathrm{T}} = 0.5 \times \mathrm{C}_{\mathrm{capex,vehicles}} \tag{12}$$

Where S_{T} is the salvage value [€], $\mathrm{C}_{\mathrm{capex,vehicles}}$ is the initial cost of vehicles [€].

The salvage value of refuelling-station infrastructure is omitted because its expected service life (e.g., 15–20 years) far exceeds our five-year study horizon, making any remaining value highly uncertain and negligible for the analysis.

These calculations form the basis for comprehensive comparative evaluations between hydrogen, biogas, and diesel-powered vehicles. However, recognizing that input parameters such as fuel efficiency and infrastructure-related costs may vary in practical situations, it is essential to assess the robustness of the calculated results. Therefore, the following subsection will describe how sensitivity analyses will be conducted to understand the potential impact of key variables on the final TCO values.

3.2 Sensitivity analysis

Sensitivity analysis is conducted to evaluate the robustness of the TCO model under varying conditions. This involves analyzing the impact of key parameters on total costs.

Assessing how variations in fuel efficiency ± 5 % influence the overall TCO. This study also analyses the impact of fluctuating construction costs for refuelling stations, varying by ± 10 %. These cost changes can significantly influence the TCO.

In addition to fuel efficiency and station costs, factors such as fuel price trends, toll policy changes, and labor cost fluctuations could significantly influence the TCO. For instance, if diesel prices continue to rise due to carbon taxes or geopolitical instability (Hossein et al., 2021), the competitiveness of hydrogen and biogas may improve faster than projected. Similarly, technological breakthroughs, such as improvements in electrolyzer efficiency or cost reductions in cryogenic storage, can drastically lower the TCO of hydrogen and LBG vehicles. It is also important to note that different regions may offer targeted incentives or exemptions (e.g., toll reductions for zero-emission vehicles), which can change the financial landscape for fleet operators.

Results from the sensitivity analysis provide insights into the most critical cost drivers and help decision-makers better understand potential risks and uncertainties. The computational analysis, implemented in MATLAB, builds upon the parameters and assumptions outlined in this section.

4 Results and discussion

This section presents the calculation results for the TCO per kilometre for hydrogen, biogas, and diesel-operated HDVs based on the assumptions and methods outlined in the previous sections. It also includes the results from sensitivity analyses of key parameters such as fuel efficiency and refuelling station costs.

4.1 Total cost of ownership per kilometre and cost breakdown analysis

Table 9 summarizes the TCO per kilometre results calculated for hydrogen, biogas, and diesel-powered vehicles and presents the final TCO per kilometre.

Table 9. TCO per kilometre and cost breakdown (€/km)

Fuel Type	Vehicles CapEx	Fuel	Station CapEx	Station Maintenance	Toll	Labor	Total Cost
Hydrogen (350 bar)	0.19	0.72	6.59	1.23	0.16	0.28	9.17
Hydrogen (700 bar)	0.24	1.09	4.40	0.82	0.17	0.28	7.00
Biogas (CBG)	0.12	0.67	3.17	1.37	0.16	0.28	5.79
Biogas (LBG)	0.14	0.85	1.59	0.69	0.18	0.28	3.73
Diesel	0.13	0.59	0	0.05	0.18	0.28	1.24

In addition to the cost-per-kilometre breakdown in Table 9, Table 10 presents the absolute five-year total costs (in euros) for each fuel type. This allows a clearer understanding of the overall financial scale of each cost component.

Table 10. Absolute five-year costs for each fuel type (€)

Fuel Type	Vehicles CapEx	Fuel	Station CapEx	Station Maintenance	Toll	Labor	Total Cost
Hydrogen (350 bar)	155,610	589,680	5,397,210	1,007,370	131,040	229,320	7,510,230
Hydrogen (700 bar)	196,560	892,710	3,603,600	671,580	139,230	229,320	5,733,000
Biogas (CBG)	98,280	548,730	2,596,230	1,122,030	131,040	229,320	4,725,630
Biogas (LBG)	114,660	696,150	1,302,210	565,110	147,420	229,320	3,054,870
Diesel	106,470	483,210	0	40,950	147,420	229,320	1,007,370

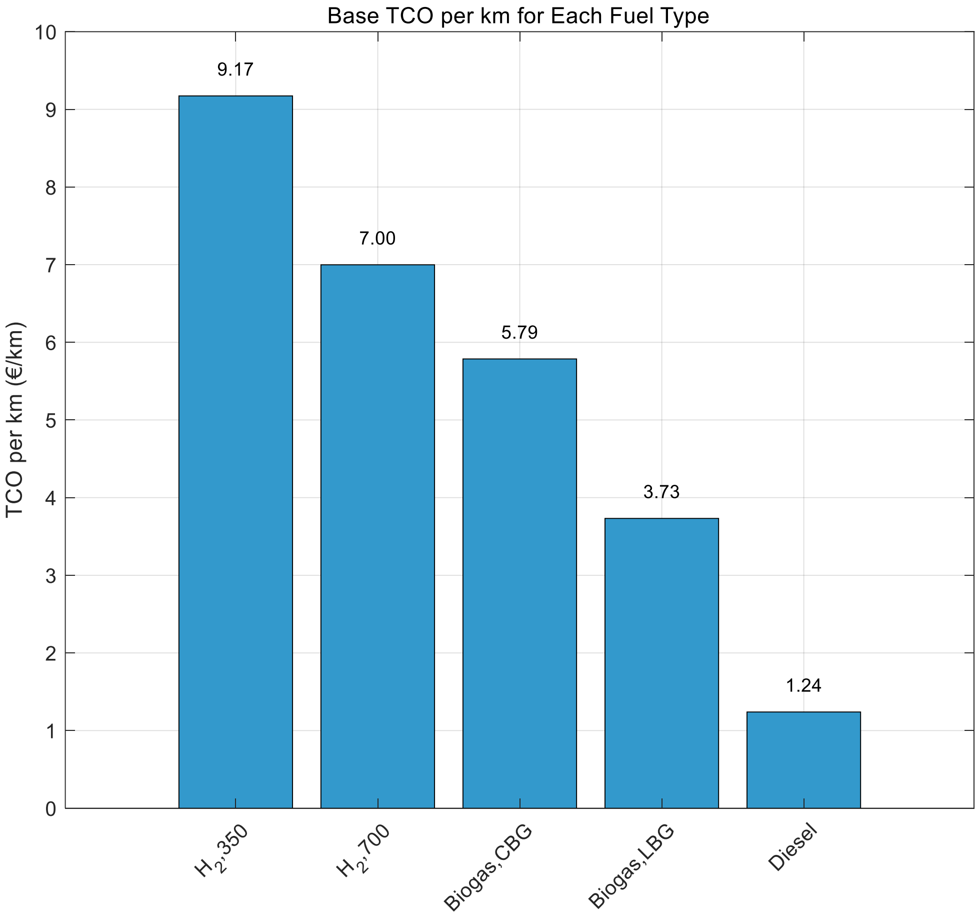

Figure 9. Total Cost of Ownership per kilometre for each fuel type.

Figure 9 shows the comparison of TCO per kilometre for different fuel types. The chart clearly illustrates that hydrogen-powered vehicles, especially at 350 bar pressure, currently have the highest costs per kilometre, mainly due to high fuel prices and infrastructure investments. Biogas vehicles, particularly LBG, present significantly lower TCO, highlighting their economic feasibility as sustainable alternatives. Diesel vehicles still offer the lowest TCO from a purely economic perspective, but face increasing environmental regulatory pressures.

The cost breakdown analysis clearly presents the cost of each fuel. The bar chart is presented in Figure.

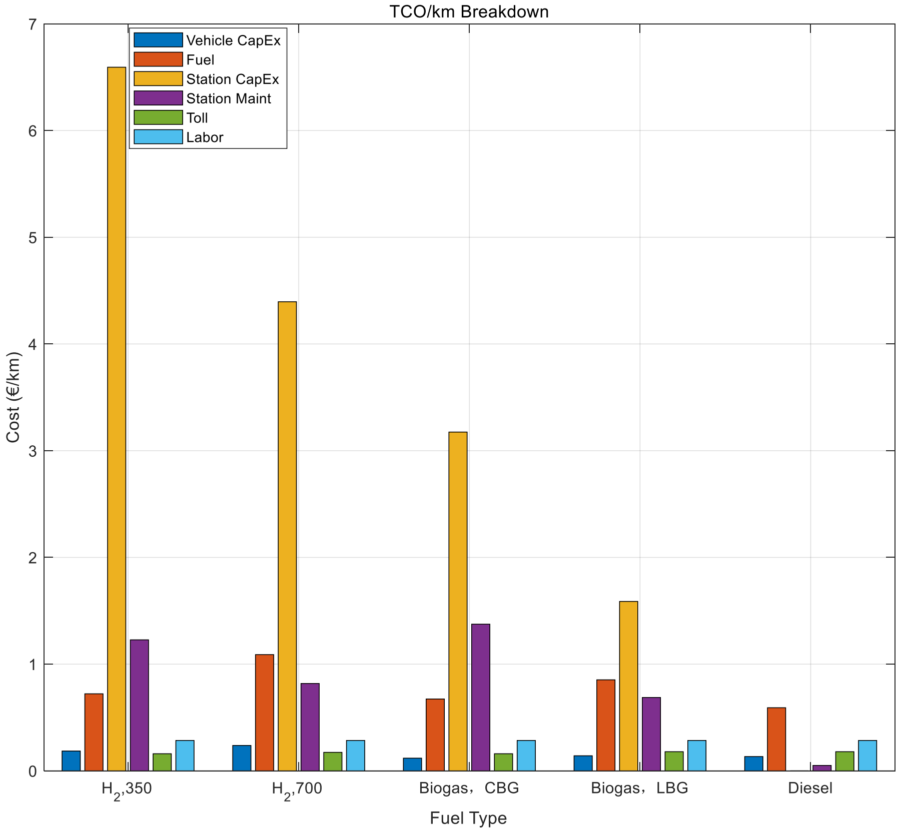

Figure 10. Cost breakdown of TCO/km for each fuel type.

As clearly indicated in Figure 9 and 10, hydrogen-powered HDVs have the highest TCO per kilometer, especially 350 bar hydrogen, primarily due to 350 bar hydrogen’s short vehicle range, which requires more refuelling stations in the study route and relatively high fuel price. Conversely, biogas-powered HDVs have lower TCO per kilometre, benefiting from lower fuel prices and high vehicle range, which need fewer refuelling stations. Diesel-powered HDVs have the lowest TCO per kilometre. The value of TCO per kilometre for diesel fuel is minimal due to a well-developed refuelling station system. So, from the result, we can see that refuelling stations significantly impact TCO per kilometre. Table 11 shows the total costs without considering the costs of refueling infrastructure.

Table 11. TCO per kilometre (no refuelling station) (€/km)

Fuel Type	Total cost (no refuelling station)
Hydrogen (350 bar)	1.35
Hydrogen (700 bar)	1.78
Biogas (CBG)	1.24
Biogas (LBG)	1.46
Diesel	1.19

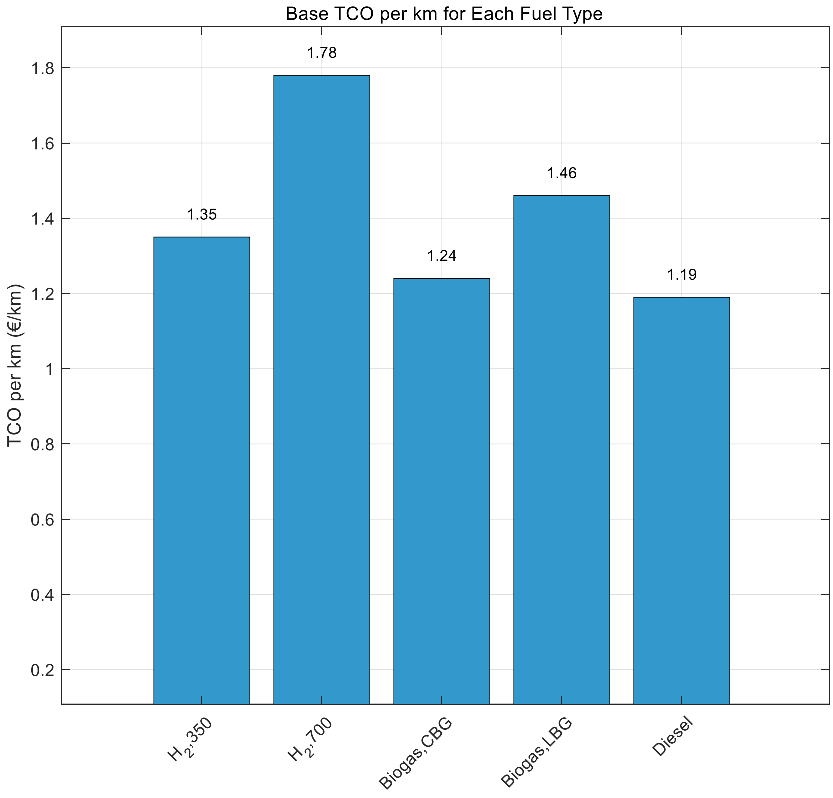

Figure 11. TCO per kilometre for each fuel type (no refuelling station).

Figure 11 and Table 11 show a comparison of TCO per kilometre for each fuel type without refuelling station costs. This figure illustrates that the TCO differences among the fuel types become narrower when infrastructure costs for refueling stations are excluded. Hydrogen vehicles at 700 bar still maintain the highest costs, predominantly due to higher fuel prices and vehicle investment. Biogas (CBG) vehicles emerge as the most economically favourable option, closely followed by diesel vehicles, which benefit from established market conditions and lower initial vehicle costs. This scenario emphasizes that infrastructure investments significantly impact the economic competitiveness of alternative fuels, particularly for hydrogen.

Figure 12 illustrates the breakdown of the TCO per kilometre, excluding refuelling station costs, to better understand the distribution of cost components for each fuel type.

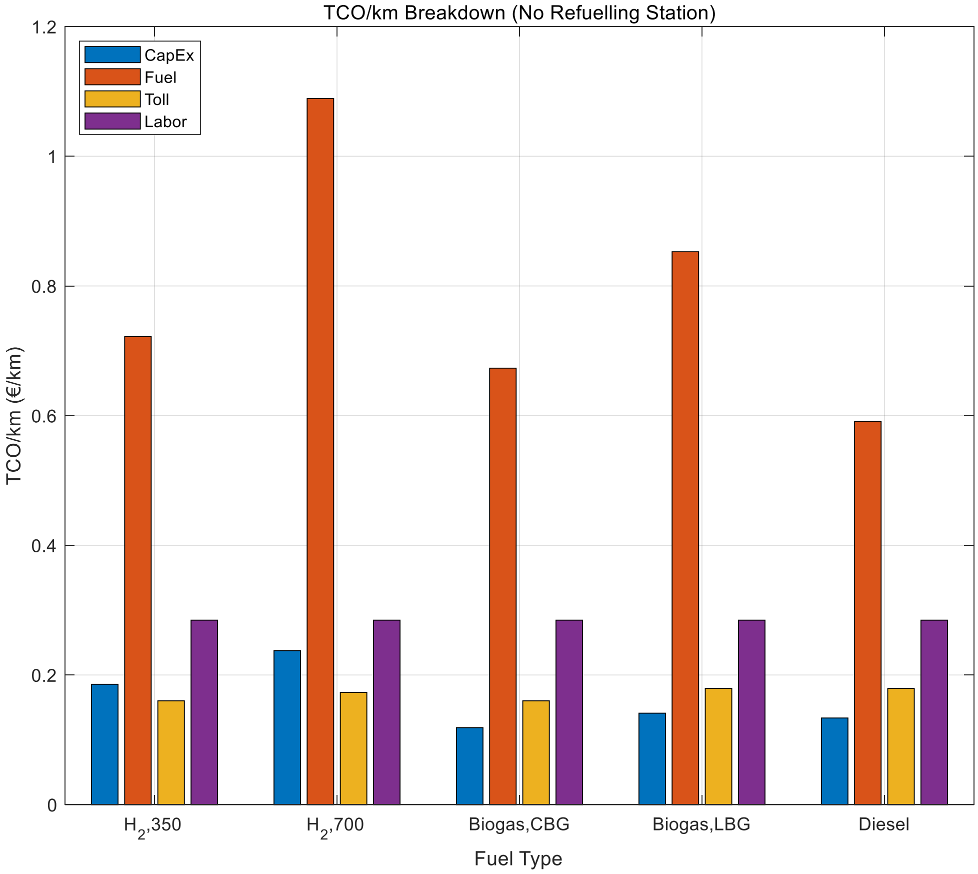

Figure 12. Cost breakdown of TCO/km for each fuel type (without refuelling station).

As depicted in Figure 12, this breakdown makes it abundantly evident that energy prices account for the largest share of overall operating expenses of all fuel kinds. The need for cost reduction in hydrogen production and distribution is highlighted by the much higher fuel-related expenses of hydrogen-powered vehicles, particularly at 700 bar, compared to other options. With modest fuel, labor, and capital expenses, biogas vehicles CBG and LBG have relatively balanced cost distributions, with fuel, labor, toll, and capital costs contributing more evenly than hydrogen or diesel vehicles. Although diesel prices are still high, diesel vehicles are competitive due to their fuel infrastructure and reduced upfront costs. These findings highlight how fuel cost dynamics significantly impact the feasibility of using alternative energy sources for heavy-duty transportation.

4.2 Sensitivity analysis

Sensitivity analysis identifies fuel efficiency and refuelling station prices as crucial elements that evaluate the robustness of the TCO results. Sensitivity assessments are essential to comprehend how these factors affect the overall economic feasibility of alternative fuels because of the inherent uncertainties in fuel prices, vehicle efficiency, infrastructure costs, and regulatory regimes. In particular, differences in fuel efficiency directly influence fuel consumption, which significantly impacts operational expenses and, thus, the TCO. Similarly, the cost of refuelling stations, which are impacted by location, laws, and technical developments, is a significant determinant of the infrastructure investment.

A thorough sensitivity analysis aids stakeholders in strategically prioritizing investments and enhancements and offers insightful information about the important variables affecting decision-making. By measuring how changes in important factors might affect the financial results, stakeholders can better grasp the potential and hazards of switching to hydrogen, biogas, or diesel for HDVs operations. Table 12 demonstrates the impact of a ± 5 % change in fuel efficiency on the TCO per kilometre for each fuel type.

Table 12. Fuel Efficiency Sensitivity Analysis (€/km)

Efficiency Variation	Hydrogen (350 bar)	Hydrogen (700 bar)	Biogas (CBG)	Biogas (LBG)	Diesel
- 5 %	9.14	6.94	5.75	3.70	1.21
Base Case (0 %)	9.17	7.00	5.79	3.73	1.24
+ 5 %	9.21	7.05	5.82	3.77	1.27

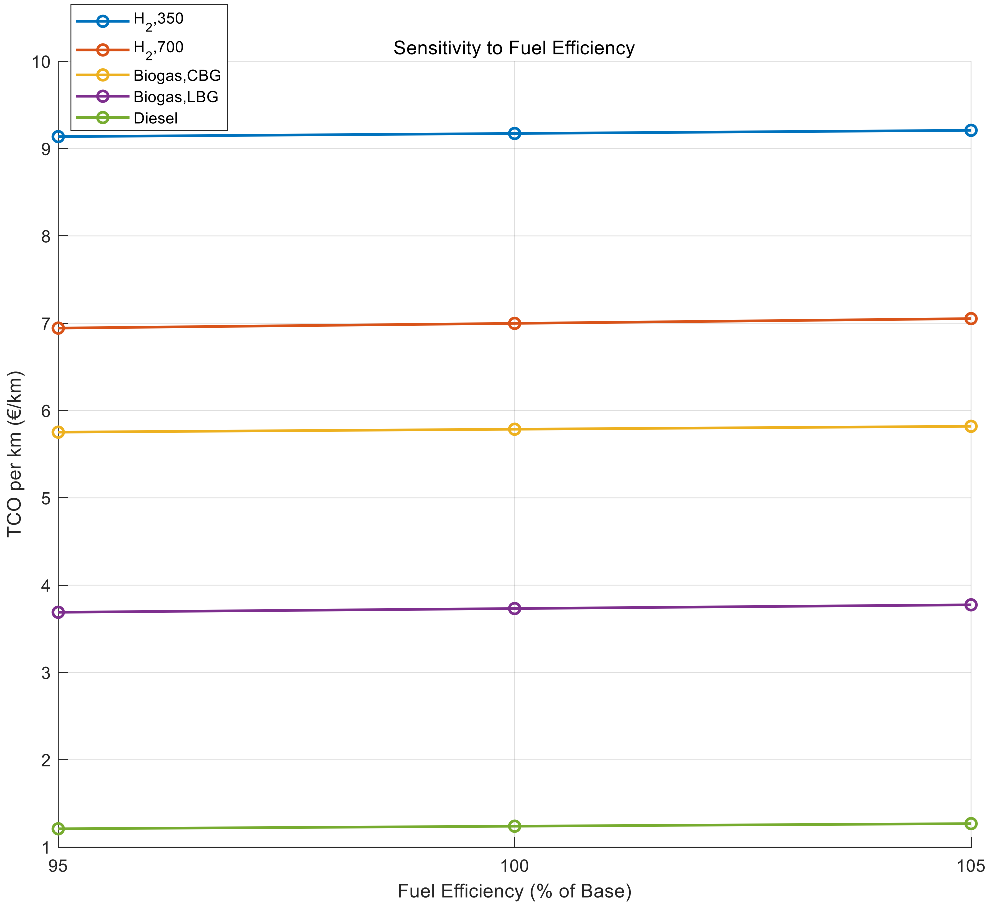

Figure 13. Fuel efficiency sensitivity analysis.

According to the sensitivity study, hydrogen is more sensitive to changes in fuel efficiency, mainly because its high fuel cost accounts for most of the total operating costs. Even modest increases in fuel economy can significantly reduce fuel consumption, thus dramatically lowering the TCO. Furthermore, the technology now used in hydrogen-powered vehicles is less developed, offering more room for efficiency improvements.

Diesel and biogas, on the other hand, are comparatively less sensitive. Efficiency gains have a noticeable but less noticeable impact on the TCO since biogas fuel, although less expensive than hydrogen, still has considerable cost contributions from fuel expenditures. Diesel has the least sensitivity since it already benefits from a well-established, economical infrastructure and comparatively lower fuel rates. Since fuel-related costs account for a lesser percentage of diesel vehicles' overall cost structure than hydrogen, incremental efficiency gains in these vehicles only result in modest cost reductions.

Concentrating on improving technological and operational efficiency is thus especially important for hydrogen vehicles to become more economically viable and competitive in the market. Table 13 presents the TCO/km sensitivity analysis results concerning changes in the construction of refuelling stations ± 10 % for hydrogen and biogas vehicles.

Table 13. Refuelling Station Sensitivity (€/km)

Station Cost Variation	Hydrogen (350 bar)	Hydrogen (700 bar)	Biogas (CGB)	Biogas (LBG)
- 10 %	8.39	6.48	5.33	3.50
Base Case (0 %)	9.17	7.00	5.79	3.73
+ 10 %	9.96	7.52	6.24	3.96

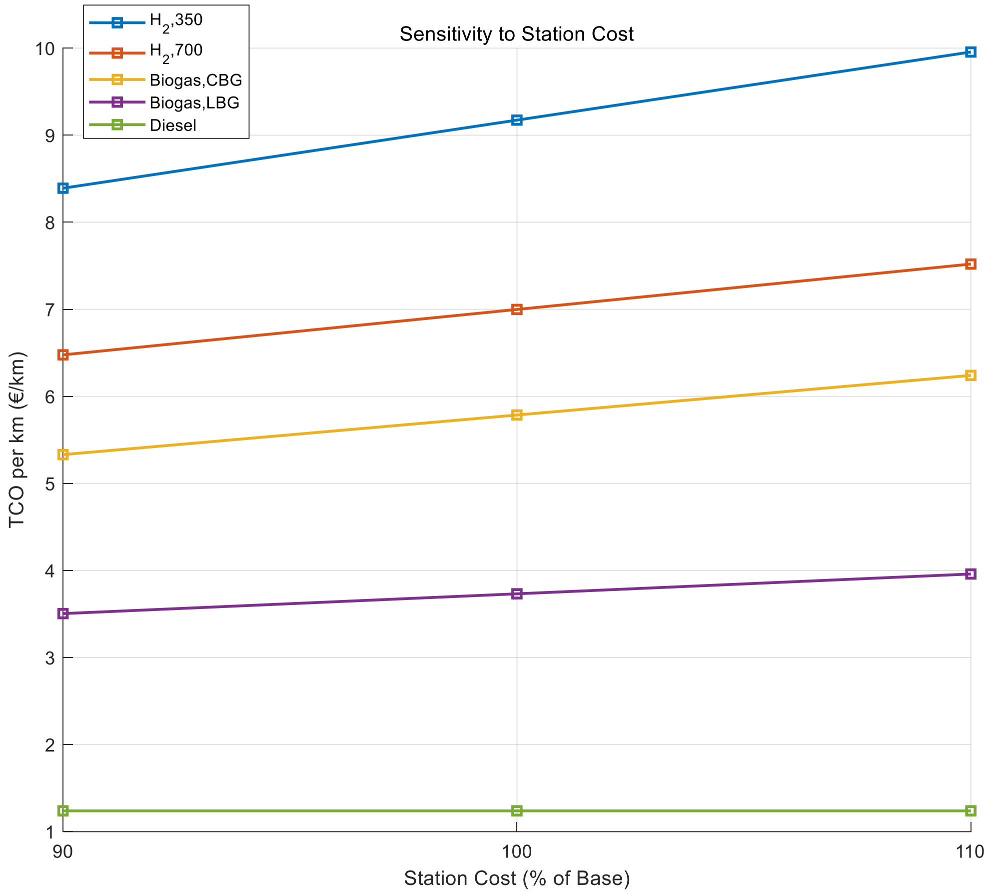

Figure 14. Refuelling station sensitivity analysis.

Figure 14 highlights the sensitivity of TCO per kilometre to variations in refuelling station construction costs. The high initial cost and ongoing maintenance of hydrogen refuelling facilities make hydrogen-powered vehicles more sensitive, especially above 350 bar. Even small changes in infrastructure expenses can significantly impact the economic feasibility of hydrogen as a fuel choice. Compared to hydrogen, biogas vehicles (CBG and LBG) exhibit observable, albeit reduced, sensitivity, showing that infrastructure expenses have less impact on their economic viability. As diesel refuelling infrastructure is already mature, widely accessible, and relatively low-cost, diesel vehicles are not the primary focus of this study.

Sensitivity analysis emphasizes the significance of strategic infrastructure investment planning, possible government subsidies, and technology improvements to reduce initial and ongoing infrastructure-related costs, especially for hydrogen. In the heavy-duty transportation industry, lowering infrastructure costs would significantly increase the appeal and competitiveness of alternative fuel vehicles.

A radar graphic was created to further visualize and combine the sensitivity analysis of fuel efficiency and refilling station expenses. This thorough visual depiction allows one to simultaneously compare the relative sensitivity of several fuel types, amply illustrating the financial impact of altering these crucial factors.

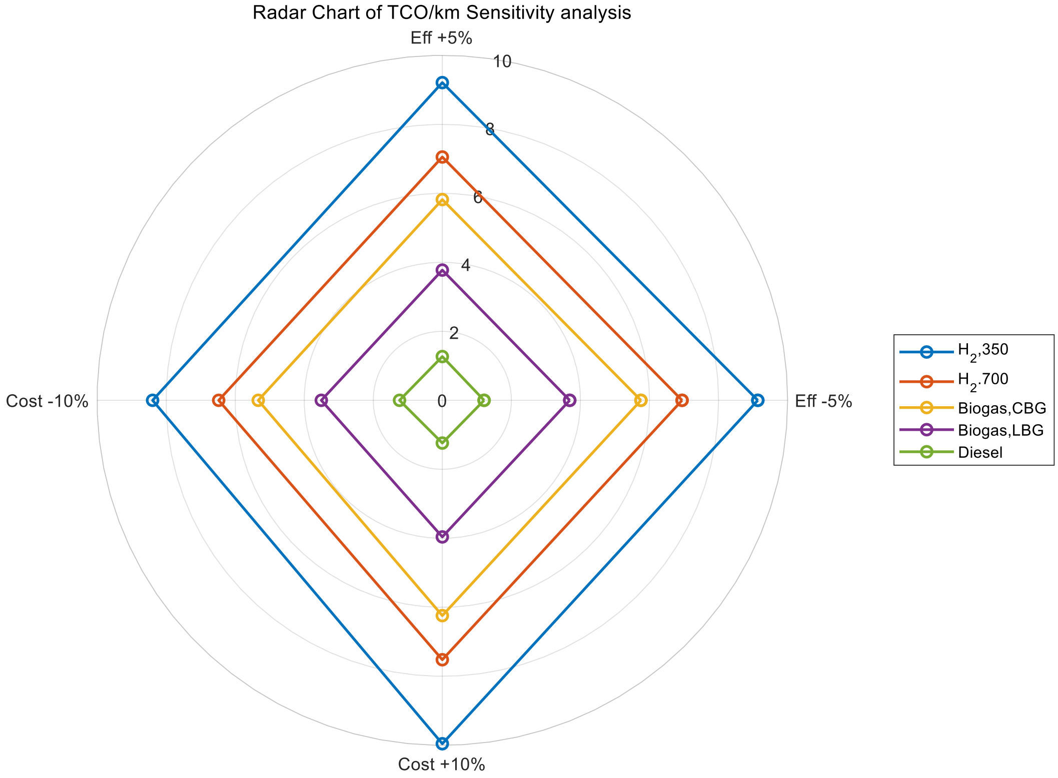

Figure 15: Radar chart illustrating TCO per kilometre sensitivity.

The most excellent sensitivity range is evident in hydrogen-powered vehicles, particularly at 350 bar, as illustrated in Figure 15. This demonstrates the significant influence of both efficiency gains and station cost fluctuations on their TCO. The comparatively broad region that hydrogen (350 bar) encompasses emphasizes its susceptibility to price swings, underscoring the necessity of supportive policies and technological advancements to reduce economic uncertainty.

Conversely, biogas vehicles exhibit a modest sensitivity level, showcasing their relatively balanced economic profile. Diesel HDVs has the lowest sensitivity region, which supports their established economic stability due to reliable fuel prices and existing infrastructure.

This radar map makes it abundantly clear that focused technological advancements and strategic investments may significantly enhance hydrogen and biogas' competitive position and economic feasibility as alternative fuels for HDV applications.

It is important to note that the presented results are subject to future developments in fuel production technologies, policy environments, and resource availability. For instance, if green hydrogen production becomes significantly more efficient through advancements such as low-cost electrolysis or large-scale integration with renewable energy, its cost competitiveness could improve rapidly. Similarly, the widespread deployment of carbon capture technologies could make blue hydrogen more viable. On the other hand, the feasibility of scaling biogas to power the entire HDV fleet may be limited by the availability of organic feedstocks. While biogas can offer a strong transitional solution, further analysis is required to assess whether its production can meet the demands of a full market conversion. Moreover, infrastructure investments and government incentives will play a critical role in shaping the actual adoption trajectories of these alternative fuels.

5 Conclusions

This study analysed techno-economics to evaluate and compare the TCO per kilometre for HDVs powered by hydrogen, biogas, and diesel. Through comprehensive calculations, sensitivity analyses, and cost breakdown evaluations, several critical insights have emerged: Biogas-powered vehicles exhibit the most advantageous TCO per kilometer, underscoring their economic feasibility attributable to reduced vehicle investments, lower fuel costs, and limited infrastructure requirements, as the studied route required only two refuelling stations for biogas vehicles. These findings establish biogas as a viable short-term substitute for diesel, particularly in regions where biogas supply chains and infrastructure are readily available. While the higher energy density of LBG makes them a good choice for long-distance transport, their expensive technology costs make them have a high TCO per kilometre, and even though CBG is cheaper in terms of cost-effectiveness, their vehicle range of up to 600 km only limits them to regional transport. However, for LBG, up to 1600 km vehicle range is good enough to replace diesel, but the infrastructure is still lacking.

Diesel-powered vehicles demonstrated the lowest TCO per kilometre despite gradually rising fuel prices linked to carbon taxes and fossil fuel restrictions. Due to low capital costs and mature infrastructure, diesel-powered vehicles currently show the lowest TCO per kilometre. Because of future stricter environmental regulations, the economic attractiveness of diesel is expected to decline.

Hydrogen-powered vehicles had the highest TCO per kilometer because of the high cost of producing green hydrogen and the large expenditures needed for the infrastructure of high-pressure recharging stations. Sensitivity analysis showed that the leading cause of hydrogen's higher TCO was infrastructure cost, and the second was fuel cost. Reducing infrastructure costs and improving system efficiency are essential to improving economic feasibility. Future developments in green hydrogen generation technology, government assistance, and economies of scale are anticipated to reduce these expenses drastically.

Sensitivity analysis further highlights how changes in fuel efficiency and refuelling infrastructure costs significantly influence the TCO of hydrogen-powered vehicles. In particular, the TCO per kilometre decreased by €0.03, from €9.17 to €9.14, when 350 bar hydrogen trucks experienced a 5 % increase in fuel economy. While seemingly small, this reduction becomes economically significant over long operational distances. In comparison, hydrogen vehicles operating at 700 bar demonstrated slightly lower but still considerable sensitivity. The increased 725 kilometer range reduced the need for infrastructure by enabling fewer refuelling stops. However, expenditures were still driven by their more expensive high-pressure hydrogen fuel and higher initial vehicle cost. A 10 % fluctuation in station costs led the TCO to vary between €6.48 and €7.52, resulting in a spread of €0.52 per kilometre. A 5 % variation in fuel efficiency caused the TCO per kilometre to change by €0.05. This confirms that although 700 bar setups are more operationally efficient than 350 bar setups, both remain susceptible to fuel and infrastructure costs. For 350 bar systems specifically, a 10 % reduction in station cost reduced TCO from €9.17 to €8.39, highlighting the critical importance of infrastructure investment and cost optimization in improving hydrogen's long-term economic feasibility.

In comparison, the sensitivity profile of biogas vehicles was more stable and balanced. With a 600 kilometre range, compressed biogas (CBG) vehicles showed moderate sensitivity to both infrastructure cost and fuel efficiency, with the TCO per kilometre changing by €0.45 and €0.03 respectively under 10 % and 5 % variations. Among all fuels analyzed, liquefied biogas (LBG) exhibited the least sensitivity with its extended 1,600 kilometre range. The TCO varied by only €0.23 per kilometre due to infrastructure cost changes and €0.04 per kilometre due to fuel efficiency changes. These findings demonstrate that biogas, particularly LBG, is a reliable and cost-effective solution in uncertain operational and market contexts. Although biogas refuelling infrastructure is still under development in certain regions, its lower sensitivity to cost fluctuations and favorable TCO characteristics make it a strong transitional alternative for decarbonizing heavy-duty transportation in the short to medium term.

Although this study conducted a thorough investigation, it faced certain limitations. The research focused exclusively on a single route (Berlin to Paris) without accounting for distinctive topographical and climatic factors influencing fuel consumption. Additionally, some larger scenario assessments considered various operational circumstances and policy frameworks, while sensitivity analyses examined variations in fuel prices and infrastructure investments.

Some future research directions should include expanding the geographic scope, considering different route conditions, incorporating biogas and renewable hydrogen into larger energy systems, thoroughly assessing lifetime emissions, and performing dynamic scenario analyses considering changing regulatory environments and technological advancements.

In conclusion, biogas holds significant short-term promise and, based on the results of this thesis, serves as the most cost-effective alternative fuel for HDVs. Despite its current economic difficulties, hydrogen possibly has long-term promise provided that supporting laws, infrastructural development, and continuous scientific advancements are made. Enabling the broad adoption of sustainable energy solutions in heavy-duty transportation would require addressing identified economic constraints via strategic investment and ongoing innovation.

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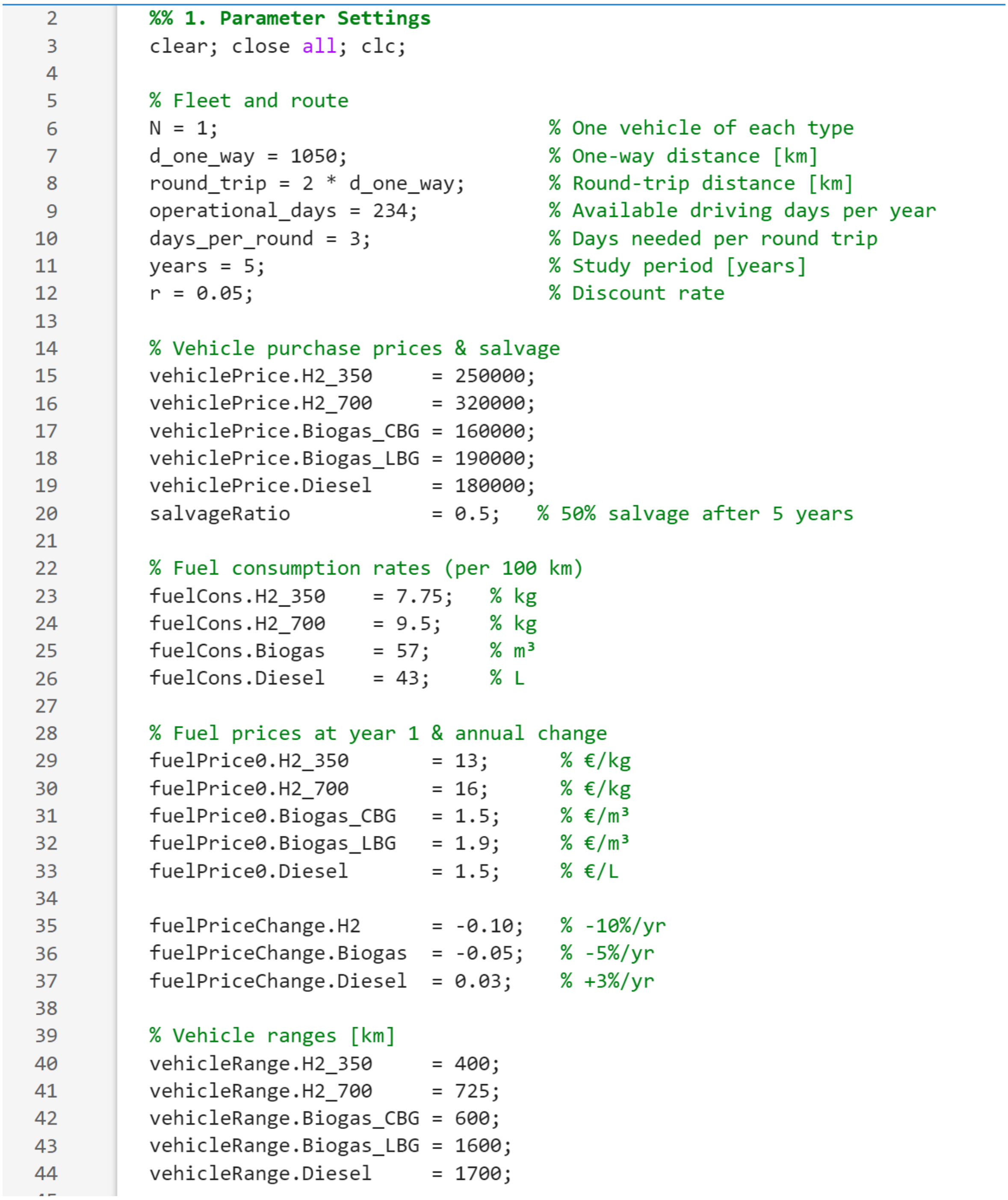
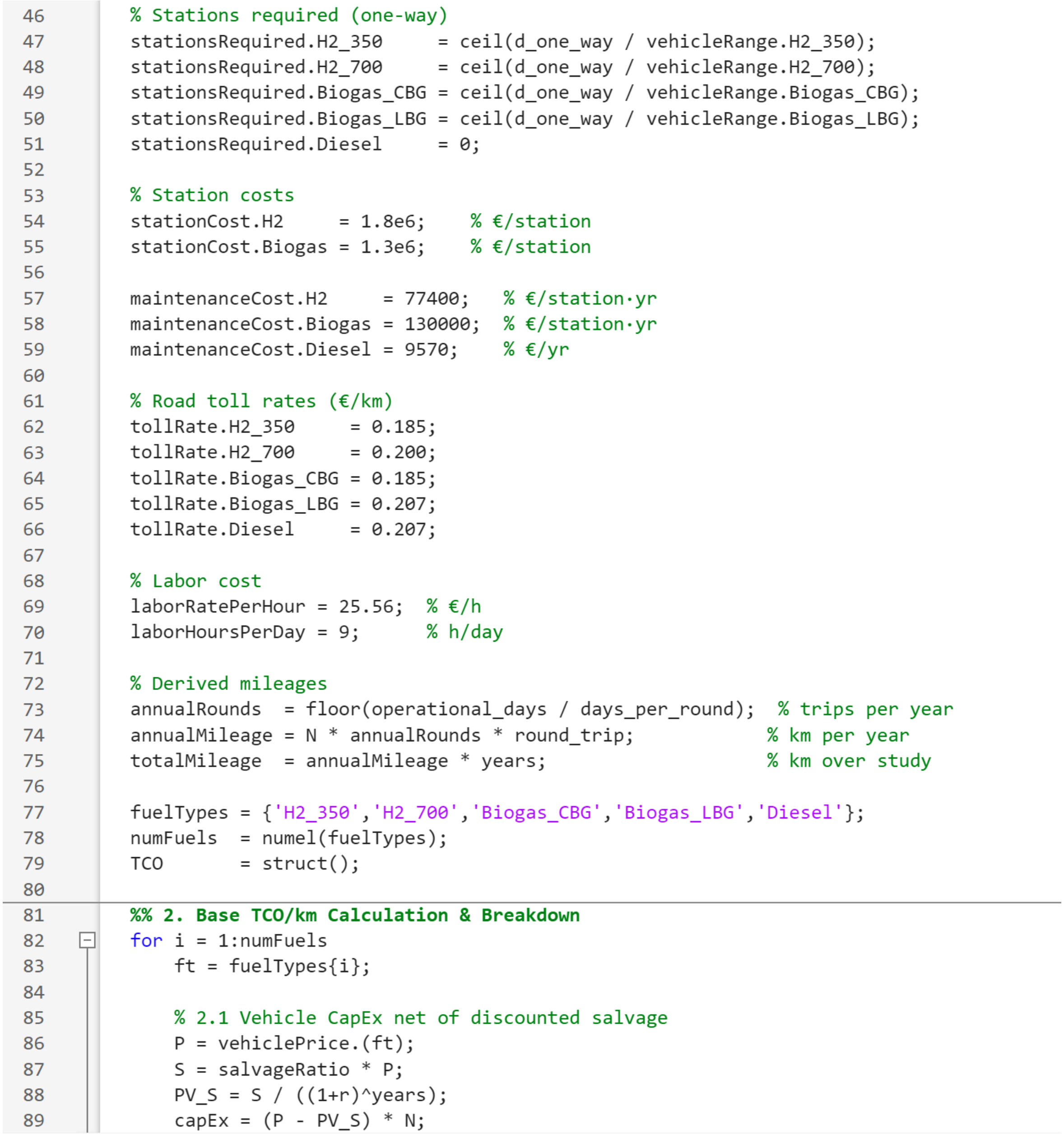
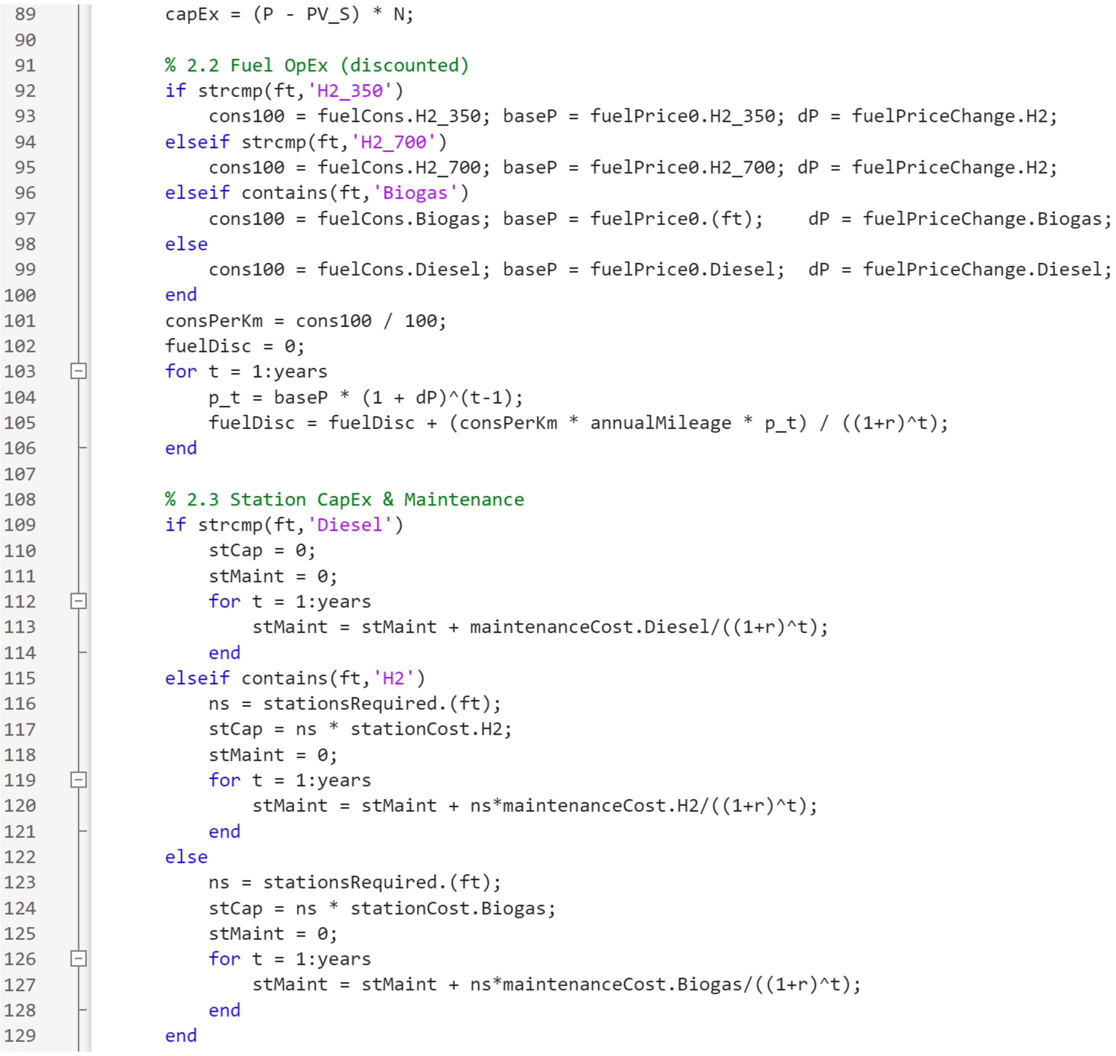
Appendix 1. TCO per kilometre, MATLAB code



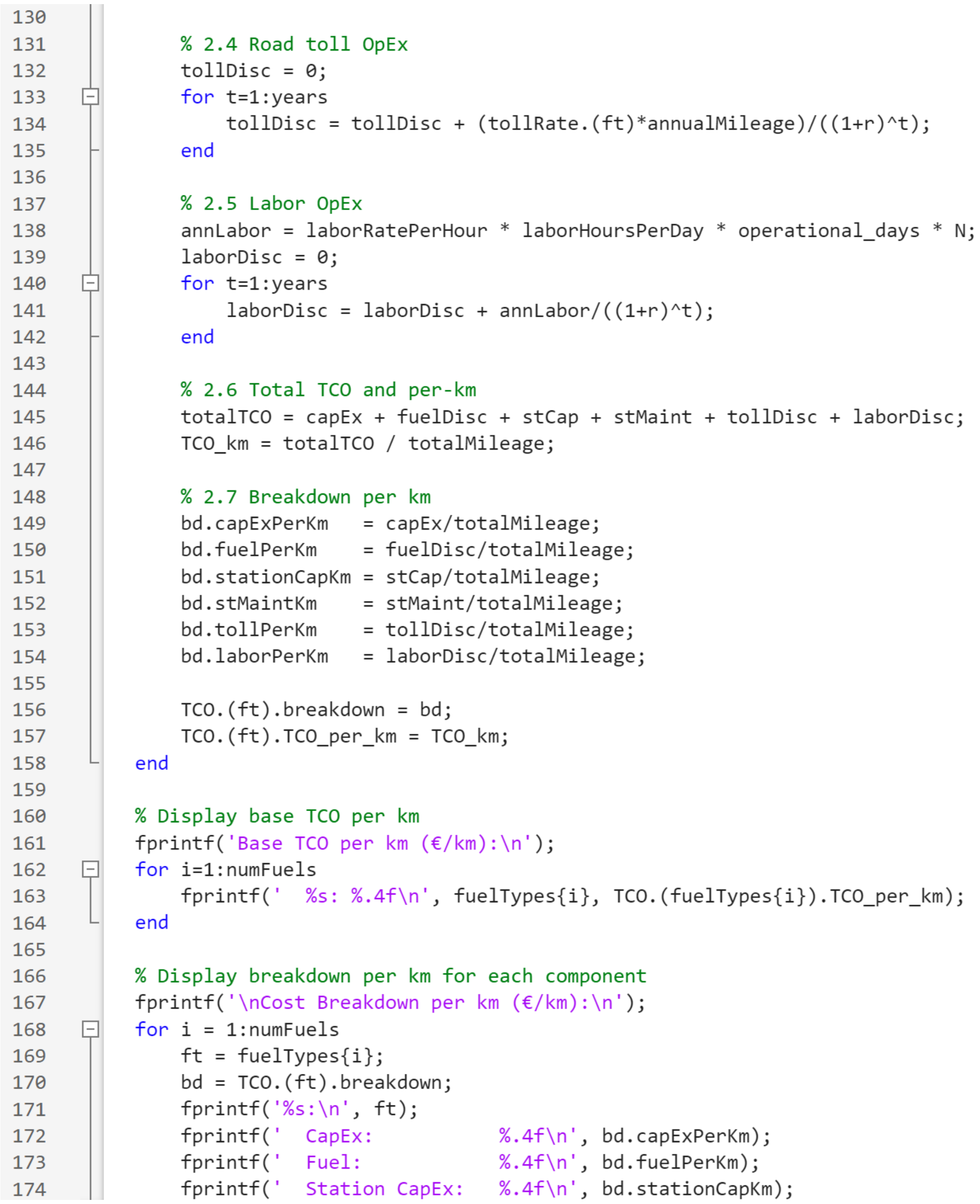
```
%% 1. Parameter Settings
clear; close all; clc;

% Fleet and route
N = 1;                            % One vehicle of each type
d_one_way = 1050;                 % One-way distance [km]
round_trip = 2 * d_one_way;       % Round-trip distance [km]
operational_days = 234;           % Available driving days per year
days_per_round = 3;               % Days needed per round trip
years = 5;                        % Study period [years]
r = 0.05;                         % Discount rate

% Vehicle purchase prices & salvage
vehiclePrice.H2_350     = 250000;
vehiclePrice.H2_700     = 320000;
vehiclePrice.Biogas_CBG = 160000;
vehiclePrice.Biogas_LBG = 190000;
vehiclePrice.Diesel     = 180000;
salvageRatio            = 0.5;   % 50% salvage after 5 years

% Fuel consumption rates (per 100 km)
fuelCons.H2_350    = 7.75;   % kg
fuelCons.H2_700    = 9.5;    % kg
fuelCons.Biogas    = 57;     % m³
fuelCons.Diesel    = 43;     % L

% Fuel prices at year 1 & annual change
fuelPrice0.H2_350       = 13;      % €/kg
fuelPrice0.H2_700       = 16;      % €/kg
fuelPrice0.Biogas_CBG   = 1.5;     % €/m³
fuelPrice0.Biogas_LBG   = 1.9;     % €/m³
fuelPrice0.Diesel       = 1.5;     % €/L

fuelPriceChange.H2      = -0.10;   % -10%/yr
fuelPriceChange.Biogas  = -0.05;   % -5%/yr
fuelPriceChange.Diesel  = 0.03;    % +3%/yr

% Vehicle ranges [km]
vehicleRange.H2_350     = 400;
vehicleRange.H2_700     = 725;
vehicleRange.Biogas_CBG = 600;
vehicleRange.Biogas_LBG = 1600;
vehicleRange.Diesel     = 1700;
```



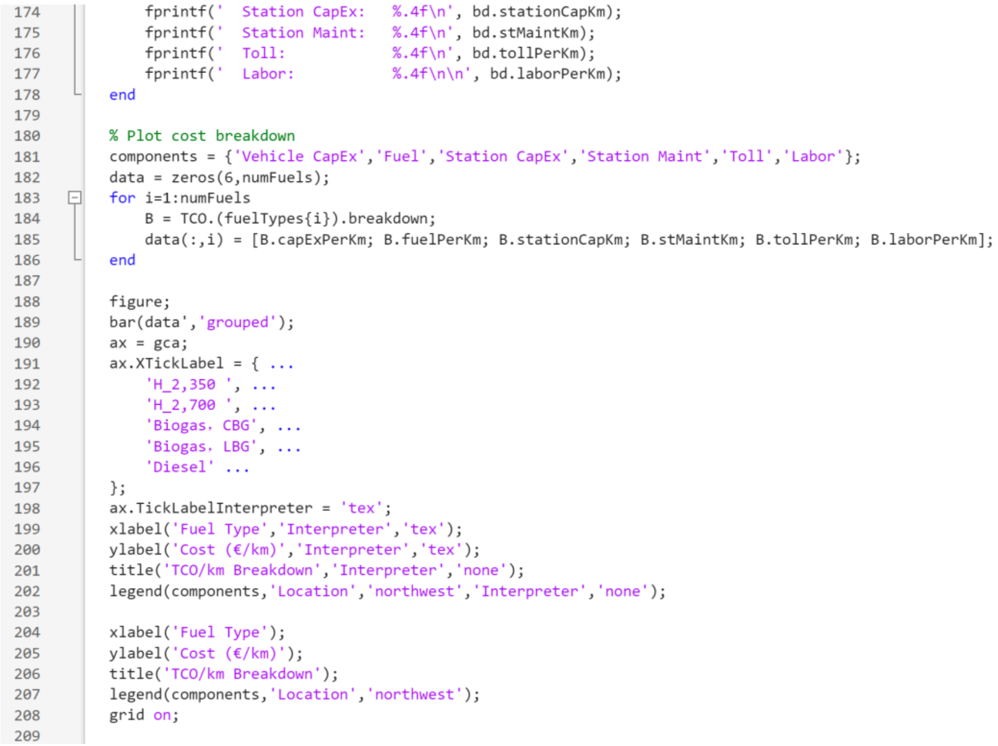
```
% Stations required (one-way)
stationsRequired.H2_350     = ceil(d_one_way / vehicleRange.H2_350);
stationsRequired.H2_700     = ceil(d_one_way / vehicleRange.H2_700);
stationsRequired.Biogas_CBG = ceil(d_one_way / vehicleRange.Biogas_CBG);
stationsRequired.Biogas_LBG = ceil(d_one_way / vehicleRange.Biogas_LBG);
stationsRequired.Diesel     = 0;

% Station costs
stationCost.H2     = 1.8e6;    % €/station
stationCost.Biogas = 1.3e6;    % €/station

maintenanceCost.H2     = 77400;   % €/station·yr
maintenanceCost.Biogas = 130000;  % €/station·yr
maintenanceCost.Diesel = 9570;    % €/yr

% Road toll rates (€/km)
tollRate.H2_350     = 0.185;
tollRate.H2_700     = 0.200;
tollRate.Biogas_CBG = 0.185;
tollRate.Biogas_LBG = 0.207;
tollRate.Diesel     = 0.207;

% Labor cost
laborRatePerHour = 25.56;  % €/h
laborHoursPerDay = 9;      % h/day

% Derived mileages
annualRounds  = floor(operational_days / days_per_round);  % trips per year
annualMileage = N * annualRounds * round_trip;            % km per year
totalMileage  = annualMileage * years;                    % km over study

fuelTypes = {'H2_350','H2_700','Biogas_CBG','Biogas_LBG','Diesel'};
numFuels  = numel(fuelTypes);
TCO       = struct();

%% 2. Base TCO/km Calculation & Breakdown
for i = 1:numFuels
    ft = fuelTypes{i};

    % 2.1 Vehicle CapEx net of discounted salvage
    P = vehiclePrice.(ft);
    S = salvageRatio * P;
    PV_S = S / ((1+r)^years);
    capEx = (P - PV_S) * N;
```



```
    capEx = (P - PV_S) * N;

    % 2.2 Fuel OpEx (discounted)
    if strcmp(ft,'H2_350')
        cons100 = fuelCons.H2_350; baseP = fuelPrice0.H2_350; dP = fuelPriceChange.H2;
    elseif strcmp(ft,'H2_700')
        cons100 = fuelCons.H2_700; baseP = fuelPrice0.H2_700; dP = fuelPriceChange.H2;
    elseif contains(ft,'Biogas')
        cons100 = fuelCons.Biogas; baseP = fuelPrice0.(ft);    dP = fuelPriceChange.Biogas;
    else
        cons100 = fuelCons.Diesel; baseP = fuelPrice0.Diesel;  dP = fuelPriceChange.Diesel;
    end
    consPerKm = cons100 / 100;
    fuelDisc = 0;
    for t = 1:years
        p_t = baseP * (1 + dP)^(t-1);
        fuelDisc = fuelDisc + (consPerKm * annualMileage * p_t) / ((1+r)^t);
    end

    % 2.3 Station CapEx & Maintenance
    if strcmp(ft,'Diesel')
        stCap = 0;
        stMaint = 0;
        for t = 1:years
            stMaint = stMaint + maintenanceCost.Diesel/((1+r)^t);
        end
    elseif contains(ft,'H2')
        ns = stationsRequired.(ft);
        stCap = ns * stationCost.H2;
        stMaint = 0;
        for t = 1:years
            stMaint = stMaint + ns*maintenanceCost.H2/((1+r)^t);
        end
    else
        ns = stationsRequired.(ft);
        stCap = ns * stationCost.Biogas;
        stMaint = 0;
        for t = 1:years
            stMaint = stMaint + ns*maintenanceCost.Biogas/((1+r)^t);
        end
    end
```

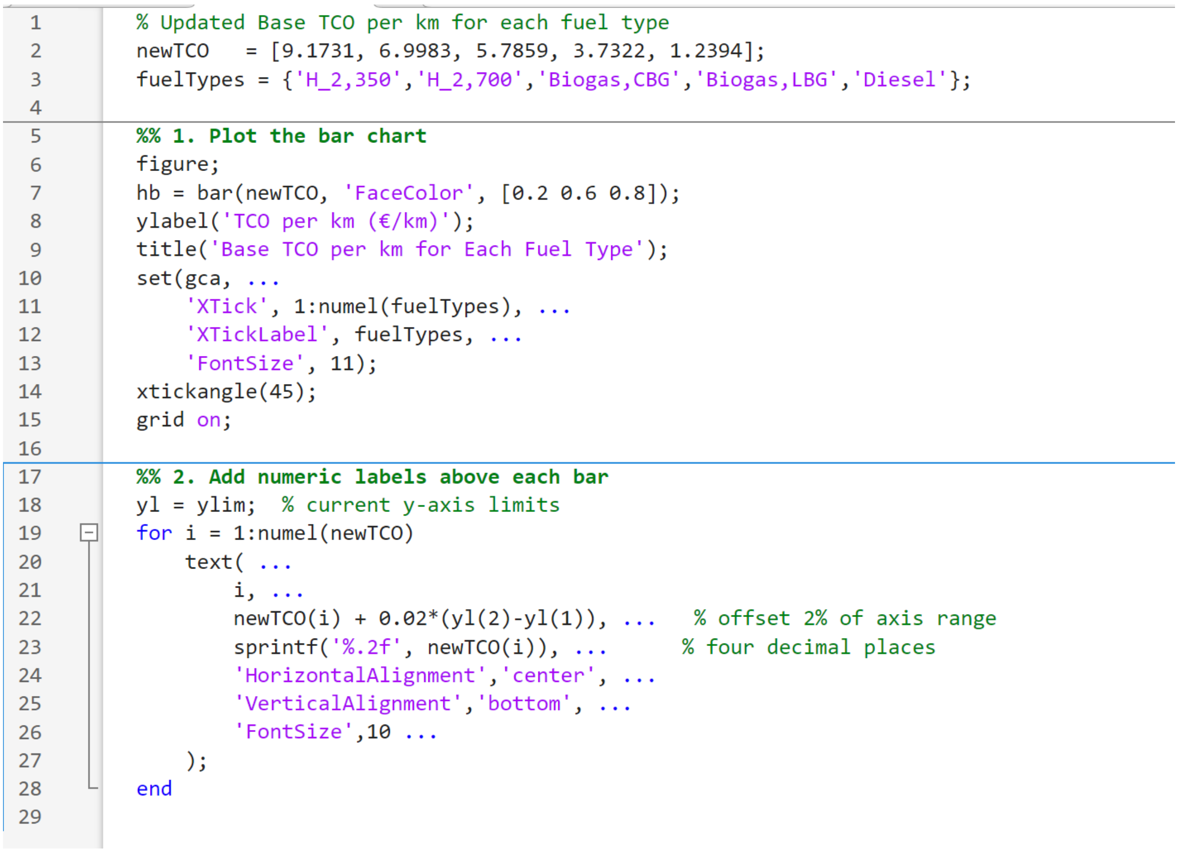


```
    % 2.4 Road toll OpEx
    tollDisc = 0;
    for t=1:years
        tollDisc = tollDisc + (tollRate.(ft)*annualMileage)/((1+r)^t);
    end

    % 2.5 Labor OpEx
    annLabor = laborRatePerHour * laborHoursPerDay * operational_days * N;
    laborDisc = 0;
    for t=1:years
        laborDisc = laborDisc + annLabor/((1+r)^t);
    end

    % 2.6 Total TCO and per-km
    totalTCO = capEx + fuelDisc + stCap + stMaint + tollDisc + laborDisc;
    TCO_km = totalTCO / totalMileage;

    % 2.7 Breakdown per km
    bd.capExPerKm   = capEx/totalMileage;
    bd.fuelPerKm    = fuelDisc/totalMileage;
    bd.stationCapKm = stCap/totalMileage;
    bd.stMaintKm    = stMaint/totalMileage;
    bd.tollPerKm    = tollDisc/totalMileage;
    bd.laborPerKm   = laborDisc/totalMileage;

    TCO.(ft).breakdown = bd;
    TCO.(ft).TCO_per_km = TCO_km;
end

% Display base TCO per km
fprintf('Base TCO per km (€/km):\n');
for i=1:numFuels
    fprintf('  %s: %.4f\n', fuelTypes{i}, TCO.(fuelTypes{i}).TCO_per_km);
end

% Display breakdown per km for each component
fprintf('\nCost Breakdown per km (€/km):\n');
for i = 1:numFuels
    ft = fuelTypes{i};
    bd = TCO.(ft).breakdown;
    fprintf('%s:\n', ft);
    fprintf('  CapEx:           %.4f\n', bd.capExPerKm);
    fprintf('  Fuel:            %.4f\n', bd.fuelPerKm);
    fprintf('  Station CapEx:   %.4f\n', bd.stationCapKm);
```



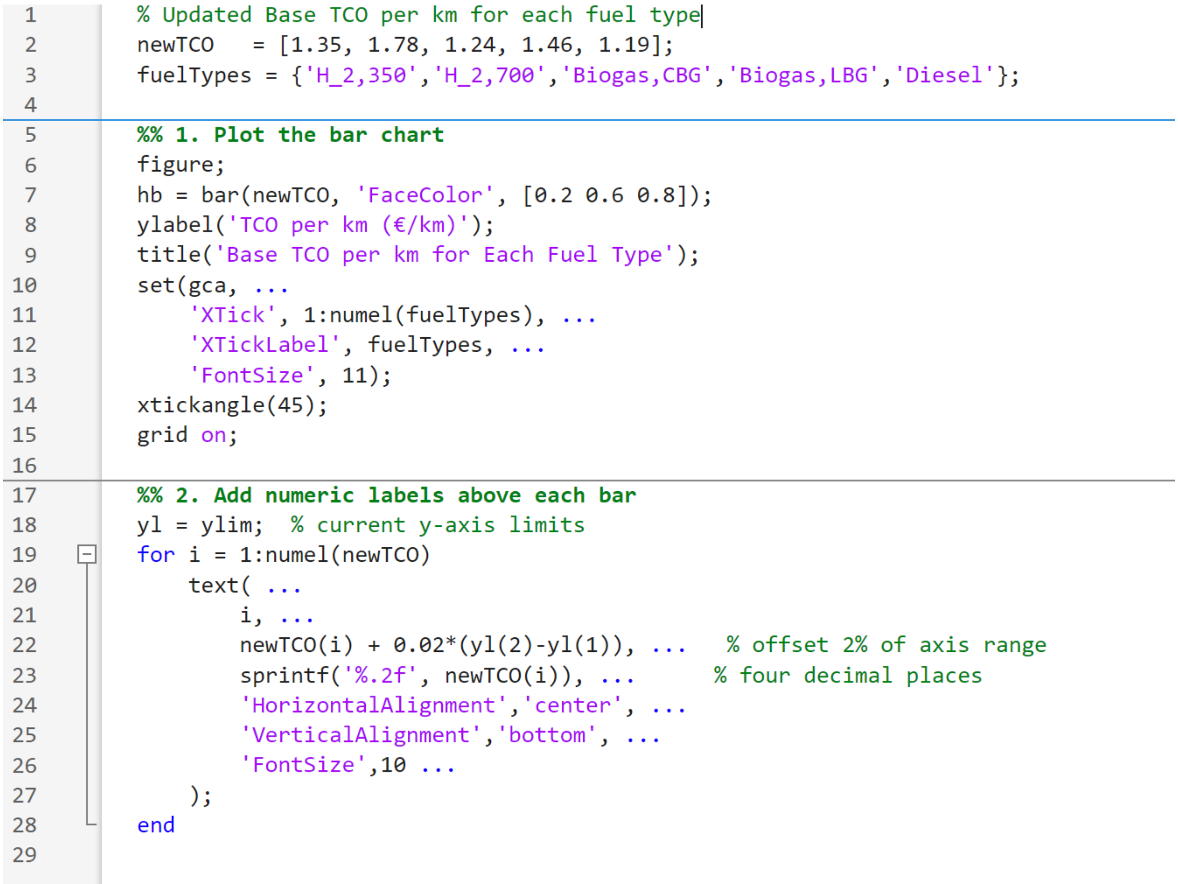
```
    fprintf('  Station CapEx:   %.4f\n', bd.stationCapKm);
    fprintf('  Station Maint:   %.4f\n', bd.stMaintKm);
    fprintf('  Toll:            %.4f\n', bd.tollPerKm);
    fprintf('  Labor:           %.4f\n\n', bd.laborPerKm);
end

% Plot cost breakdown
components = {'Vehicle CapEx','Fuel','Station CapEx','Station Maint','Toll','Labor'};
data = zeros(6,numFuels);
for i=1:numFuels
    B = TCO.(fuelTypes{i}).breakdown;
    data(:,i) = [B.capExPerKm; B.fuelPerKm; B.stationCapKm; B.stMaintKm; B.tollPerKm; B.laborPerKm];
end

figure;
bar(data','grouped');
ax = gca;
ax.XTickLabel = { ...
    'H_2,350 ', ...
    'H_2,700 ', ...
    'Biogas， CBG', ...
    'Biogas， LBG', ...
    'Diesel' ...
};
ax.TickLabelInterpreter = 'tex';
xlabel('Fuel Type','Interpreter','tex');
ylabel('Cost (€/km)','Interpreter','tex');
title('TCO/km Breakdown','Interpreter','none');
legend(components,'Location','northwest','Interpreter','none');

xlabel('Fuel Type');
ylabel('Cost (€/km)');
title('TCO/km Breakdown');
legend(components,'Location','northwest');
grid on;

```

Appendix 2. TCO per kilometre comparison, MATLAB code



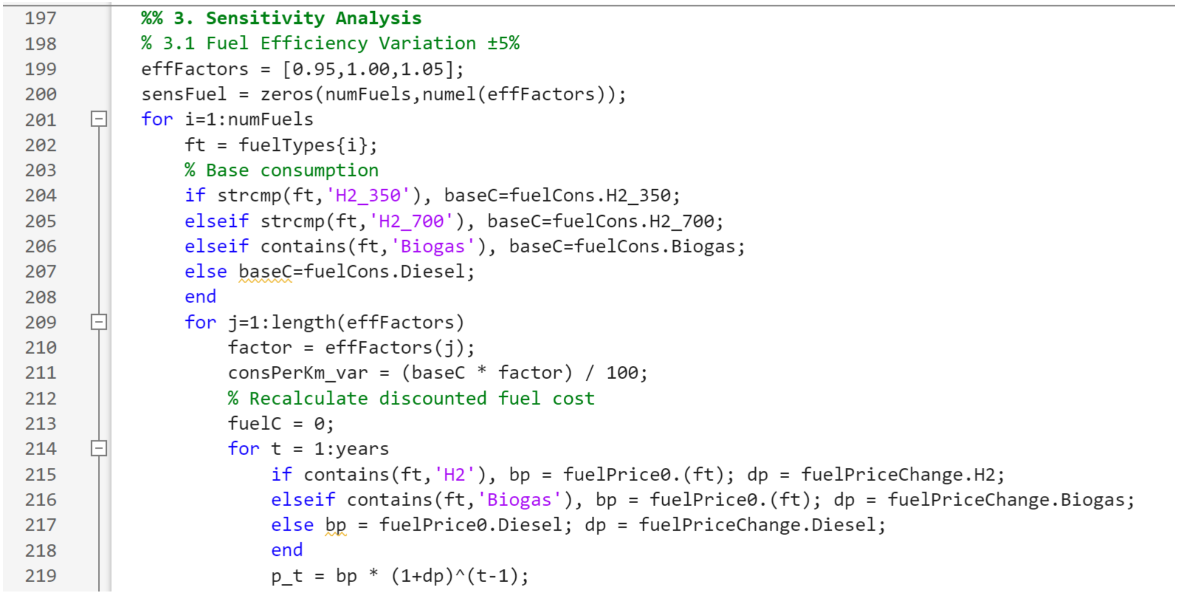
```
% Updated Base TCO per km for each fuel type
newTCO   = [9.1731, 6.9983, 5.7859, 3.7322, 1.2394];
fuelTypes = {'H_2,350','H_2,700','Biogas,CBG','Biogas,LBG','Diesel'};

%% 1. Plot the bar chart
figure;
hb = bar(newTCO, 'FaceColor', [0.2 0.6 0.8]);
ylabel('TCO per km (€/km)');
title('Base TCO per km for Each Fuel Type');
set(gca, ...
    'XTick', 1:numel(fuelTypes), ...
    'XTickLabel', fuelTypes, ...
    'FontSize', 11);
xtickangle(45);
grid on;

%% 2. Add numeric labels above each bar
yl = ylim;  % current y-axis limits
for i = 1:numel(newTCO)
    text( ...
        i, ...
        newTCO(i) + 0.02*(yl(2)-yl(1)), ...   % offset 2% of axis range
        sprintf('%.2f', newTCO(i)), ...      % four decimal places
        'HorizontalAlignment','center', ...
        'VerticalAlignment','bottom', ...
        'FontSize',10 ...
    );
end

```

Appendix 3. TCO per kilometre comparison without refuelling station cost, MATLAB code

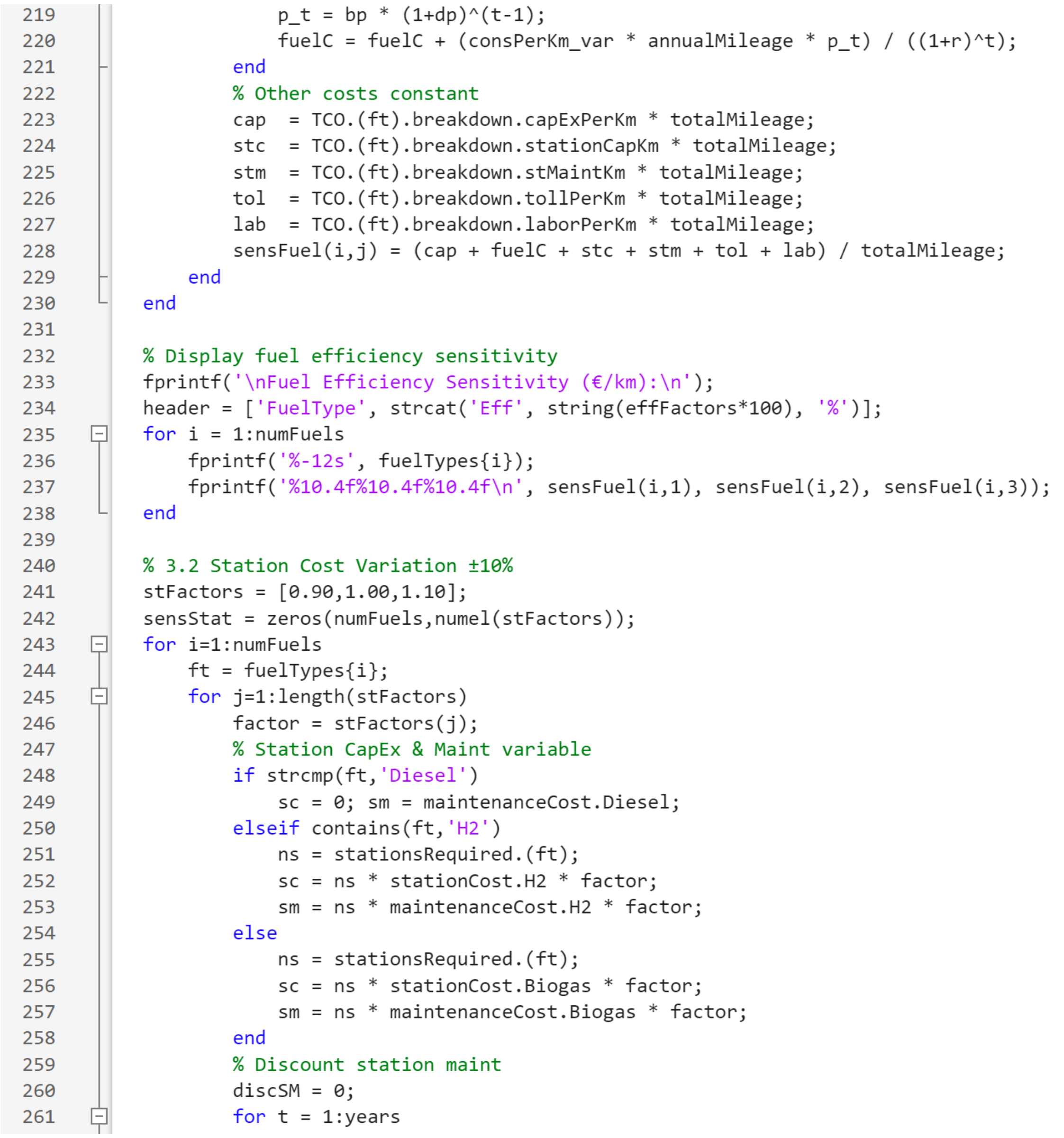


```
% Updated Base TCO per km for each fuel type
newTCO   = [1.35, 1.78, 1.24, 1.46, 1.19];
fuelTypes = {'H_2,350','H_2,700','Biogas,CBG','Biogas,LBG','Diesel'};

%% 1. Plot the bar chart
figure;
hb = bar(newTCO, 'FaceColor', [0.2 0.6 0.8]);
ylabel('TCO per km (€/km)');
title('Base TCO per km for Each Fuel Type');
set(gca, ...
    'XTick', 1:numel(fuelTypes), ...
    'XTickLabel', fuelTypes, ...
    'FontSize', 11);
xtickangle(45);
grid on;

%% 2. Add numeric labels above each bar
yl = ylim;  % current y-axis limits
for i = 1:numel(newTCO)
    text( ...
        i, ...
        newTCO(i) + 0.02*(yl(2)-yl(1)), ...   % offset 2% of axis range
        sprintf('%.2f', newTCO(i)), ...      % four decimal places
        'HorizontalAlignment','center', ...
        'VerticalAlignment','bottom', ...
        'FontSize',10 ...
    );
end

```

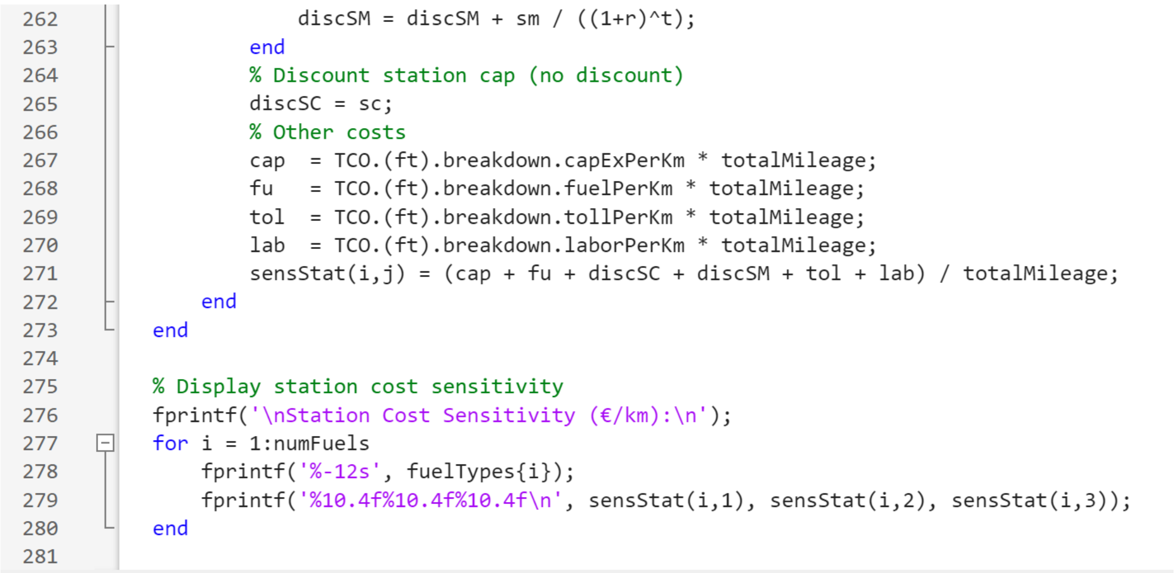
Appendix 4. Sensitivity analysis, MATLAB code



```
%% 3. Sensitivity Analysis
% 3.1 Fuel Efficiency Variation ±5%
effFactors = [0.95,1.00,1.05];
sensFuel = zeros(numFuels,numel(effFactors));
for i=1:numFuels
    ft = fuelTypes{i};
    % Base consumption
    if strcmp(ft,'H2_350'), baseC=fuelCons.H2_350;
    elseif strcmp(ft,'H2_700'), baseC=fuelCons.H2_700;
    elseif contains(ft,'Biogas'), baseC=fuelCons.Biogas;
    else baseC=fuelCons.Diesel;
    end
    for j=1:length(effFactors)
        factor = effFactors(j);
        consPerKm_var = (baseC * factor) / 100;
        % Recalculate discounted fuel cost
        fuelC = 0;
        for t = 1:years
            if contains(ft,'H2'), bp = fuelPrice0.(ft); dp = fuelPriceChange.H2;
            elseif contains(ft,'Biogas'), bp = fuelPrice0.(ft); dp = fuelPriceChange.Biogas;
            else bp = fuelPrice0.Diesel; dp = fuelPriceChange.Diesel;
            end
            p_t = bp * (1+dp)^(t-1);
```

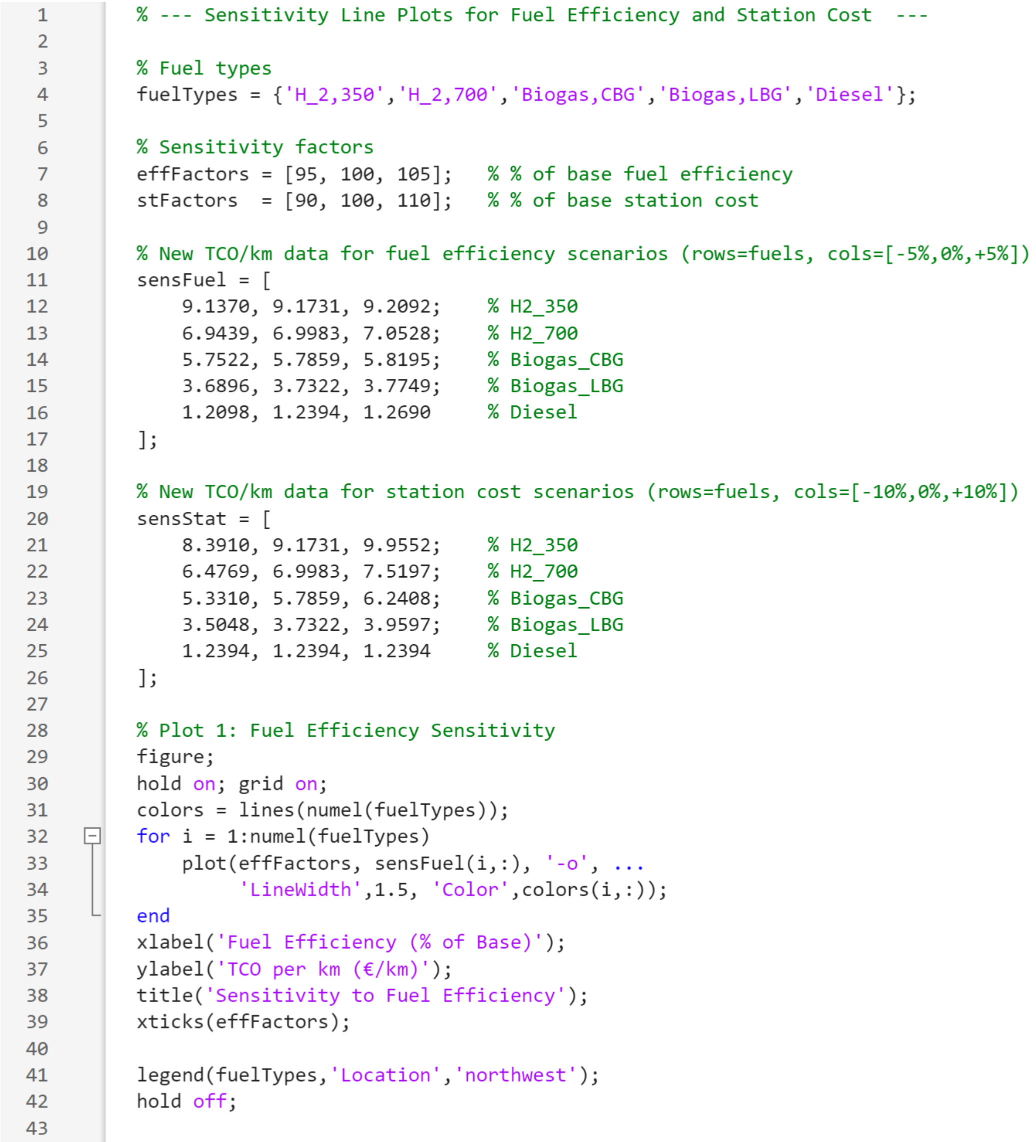


```
            p_t = bp * (1+dp)^(t-1);
            fuelC = fuelC + (consPerKm_var * annualMileage * p_t) / ((1+r)^t);
        end
        % Other costs constant
        cap  = TCO.(ft).breakdown.capExPerKm * totalMileage;
        stc  = TCO.(ft).breakdown.stationCapKm * totalMileage;
        stm  = TCO.(ft).breakdown.stMaintKm * totalMileage;
        tol  = TCO.(ft).breakdown.tollPerKm * totalMileage;
        lab  = TCO.(ft).breakdown.laborPerKm * totalMileage;
        sensFuel(i,j) = (cap + fuelC + stc + stm + tol + lab) / totalMileage;
    end
end

% Display fuel efficiency sensitivity
fprintf('\nFuel Efficiency Sensitivity (€/km):\n');
header = ['FuelType', strcat('Eff', string(effFactors*100), '%')];
for i = 1:numFuels
    fprintf('%-12s', fuelTypes{i});
    fprintf('%10.4f%10.4f%10.4f\n', sensFuel(i,1), sensFuel(i,2), sensFuel(i,3));
end

% 3.2 Station Cost Variation ±10%
stFactors = [0.90,1.00,1.10];
sensStat = zeros(numFuels,numel(stFactors));
for i=1:numFuels
    ft = fuelTypes{i};
    for j=1:length(stFactors)
        factor = stFactors(j);
        % Station CapEx & Maint variable
        if strcmp(ft,'Diesel')
            sc = 0; sm = maintenanceCost.Diesel;
        elseif contains(ft,'H2')
            ns = stationsRequired.(ft);
            sc = ns * stationCost.H2 * factor;
            sm = ns * maintenanceCost.H2 * factor;
        else
            ns = stationsRequired.(ft);
            sc = ns * stationCost.Biogas * factor;
            sm = ns * maintenanceCost.Biogas * factor;
        end
        % Discount station maint
        discSM = 0;
        for t = 1:years
```

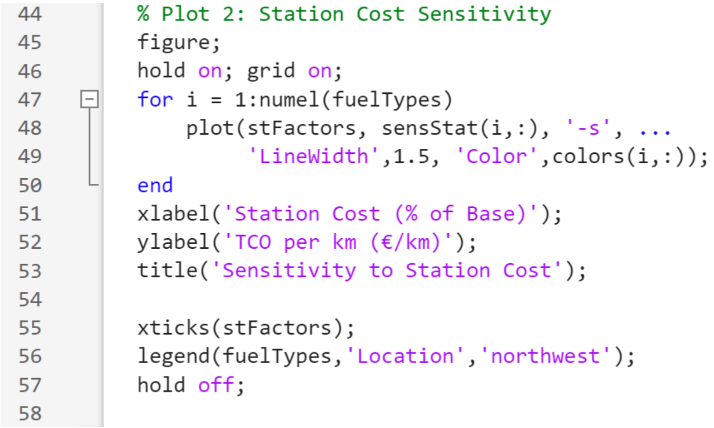


```
            discSM = discSM + sm / ((1+r)^t);
        end
        % Discount station cap (no discount)
        discSC = sc;
        % Other costs
        cap  = TCO.(ft).breakdown.capExPerKm * totalMileage;
        fu   = TCO.(ft).breakdown.fuelPerKm * totalMileage;
        tol  = TCO.(ft).breakdown.tollPerKm * totalMileage;
        lab  = TCO.(ft).breakdown.laborPerKm * totalMileage;
        sensStat(i,j) = (cap + fu + discSC + discSM + tol + lab) / totalMileage;
    end
end

% Display station cost sensitivity
fprintf('\nStation Cost Sensitivity (€/km):\n');
for i = 1:numFuels
    fprintf('%-12s', fuelTypes{i});
    fprintf('%10.4f%10.4f%10.4f\n', sensStat(i,1), sensStat(i,2), sensStat(i,3));
end
```

Appendix 5. Sensitivity line chat, MATLAB code

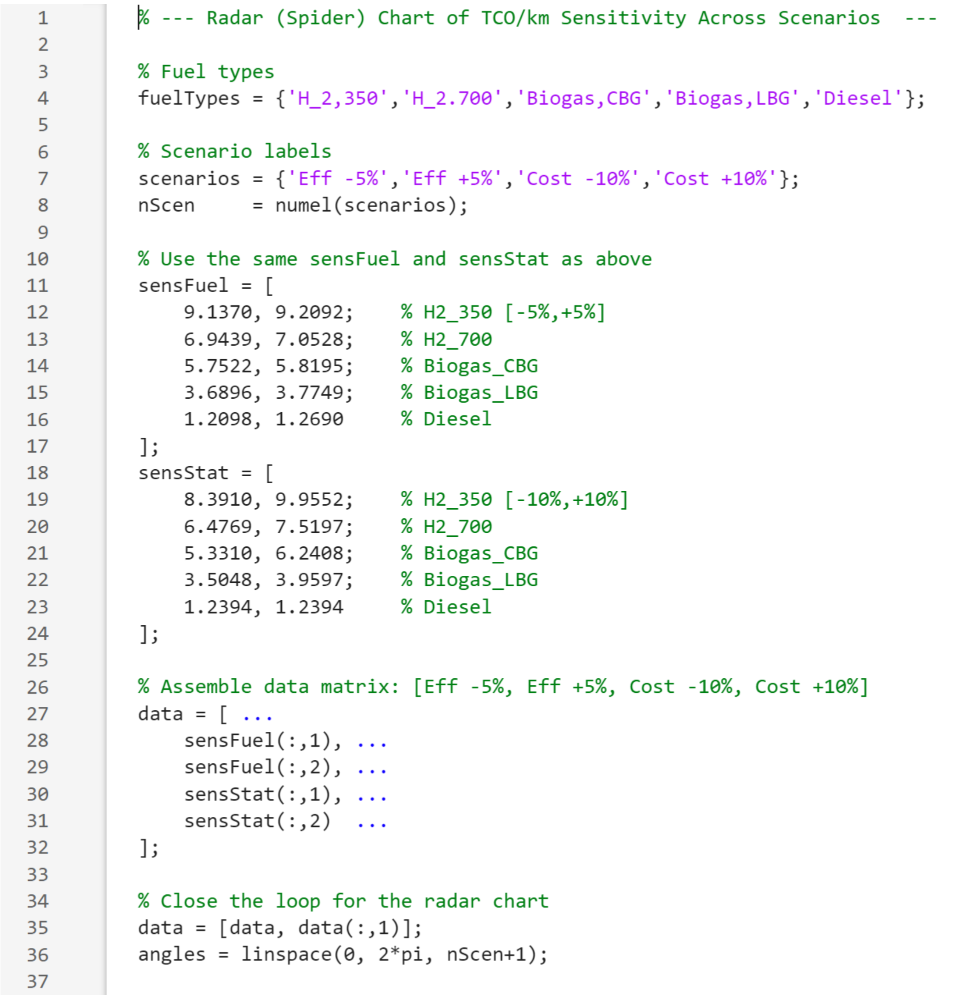


```
% --- Sensitivity Line Plots for Fuel Efficiency and Station Cost  ---

% Fuel types
fuelTypes = {'H_2,350','H_2,700','Biogas,CBG','Biogas,LBG','Diesel'};

% Sensitivity factors
effFactors = [95, 100, 105];   % % of base fuel efficiency
stFactors  = [90, 100, 110];   % % of base station cost

% New TCO/km data for fuel efficiency scenarios (rows=fuels, cols=[-5%,0%,+5%])
sensFuel = [
    9.1370, 9.1731, 9.2092;    % H2_350
    6.9439, 6.9983, 7.0528;    % H2_700
    5.7522, 5.7859, 5.8195;    % Biogas_CBG
    3.6896, 3.7322, 3.7749;    % Biogas_LBG
    1.2098, 1.2394, 1.2690     % Diesel
];

% New TCO/km data for station cost scenarios (rows=fuels, cols=[-10%,0%,+10%])
sensStat = [
    8.3910, 9.1731, 9.9552;    % H2_350
    6.4769, 6.9983, 7.5197;    % H2_700
    5.3310, 5.7859, 6.2408;    % Biogas_CBG
    3.5048, 3.7322, 3.9597;    % Biogas_LBG
    1.2394, 1.2394, 1.2394     % Diesel
];

% Plot 1: Fuel Efficiency Sensitivity
figure;
hold on; grid on;
colors = lines(numel(fuelTypes));
for i = 1:numel(fuelTypes)
    plot(effFactors, sensFuel(i,:), '-o', ...
         'LineWidth',1.5, 'Color',colors(i,:));
end
xlabel('Fuel Efficiency (% of Base)');
ylabel('TCO per km (€/km)');
title('Sensitivity to Fuel Efficiency');
xticks(effFactors);

legend(fuelTypes,'Location','northwest');
hold off;

```

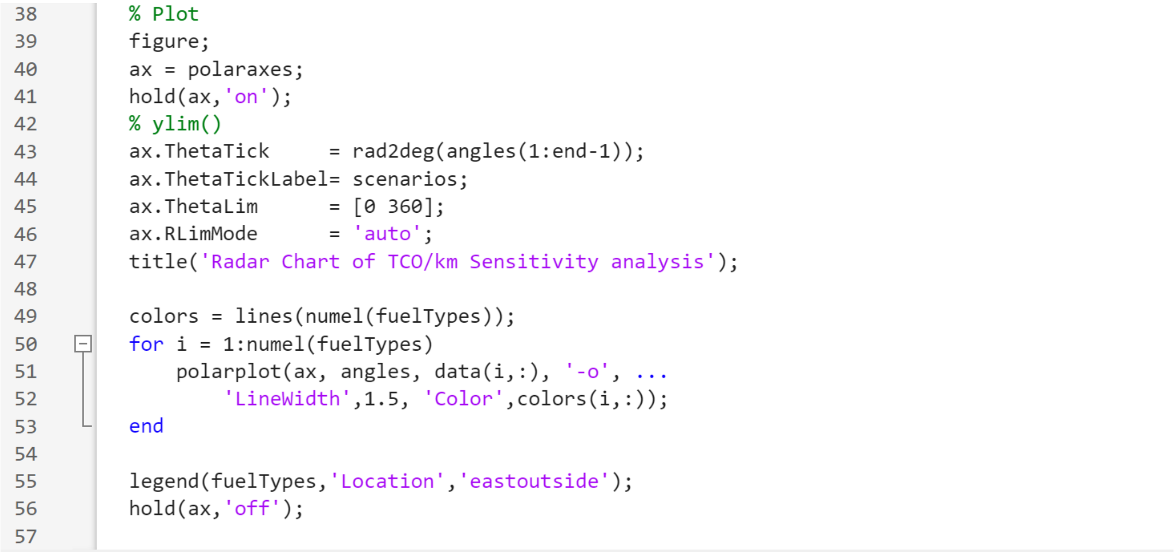


```
% Plot 2: Station Cost Sensitivity
figure;
hold on; grid on;
for i = 1:numel(fuelTypes)
    plot(stFactors, sensStat(i,:), '-s', ...
         'LineWidth',1.5, 'Color',colors(i,:));
end
xlabel('Station Cost (% of Base)');
ylabel('TCO per km (€/km)');
title('Sensitivity to Station Cost');

xticks(stFactors);
legend(fuelTypes,'Location','northwest');
hold off;

```

Appendix 6. Sensitivity radar chart, MATLAB code

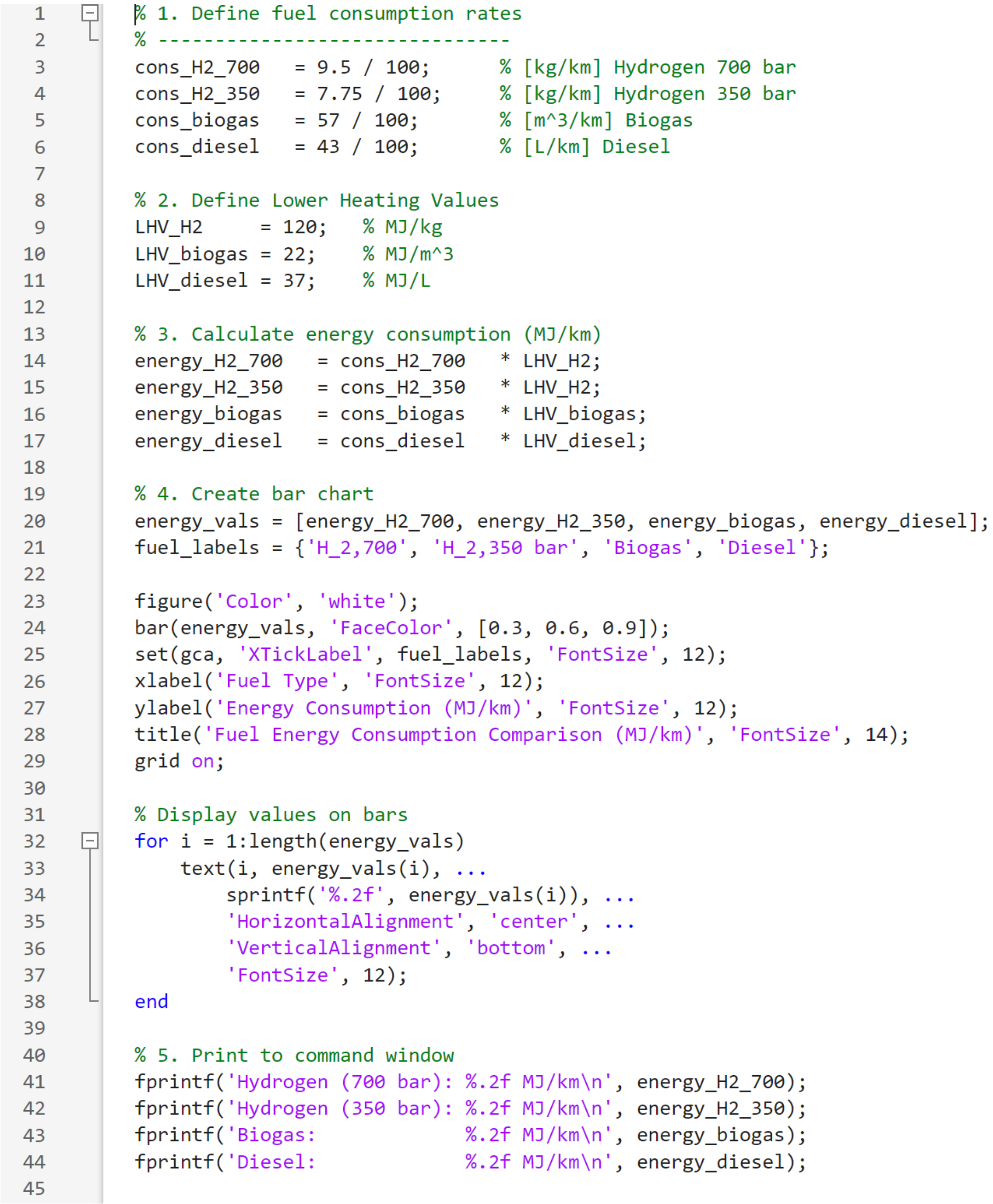


```matlab
% --- Radar (Spider) Chart of TCO/km Sensitivity Across Scenarios  ---

% Fuel types
fuelTypes = {'H_2,350','H_2.700','Biogas,CBG','Biogas,LBG','Diesel'};

% Scenario labels
scenarios = {'Eff -5%','Eff +5%','Cost -10%','Cost +10%'};
nScen     = numel(scenarios);

% Use the same sensFuel and sensStat as above
sensFuel = [
    9.1370, 9.2092;     % H2_350 [-5%,+5%]
    6.9439, 7.0528;     % H2_700
    5.7522, 5.8195;     % Biogas_CBG
    3.6896, 3.7749;     % Biogas_LBG
    1.2098, 1.2690      % Diesel
];
sensStat = [
    8.3910, 9.9552;     % H2_350 [-10%,+10%]
    6.4769, 7.5197;     % H2_700
    5.3310, 6.2408;     % Biogas_CBG
    3.5048, 3.9597;     % Biogas_LBG
    1.2394, 1.2394      % Diesel
];

% Assemble data matrix: [Eff -5%, Eff +5%, Cost -10%, Cost +10%]
data = [ ...
    sensFuel(:,1), ...
    sensFuel(:,2), ...
    sensStat(:,1), ...
    sensStat(:,2)  ...
];

% Close the loop for the radar chart
data = [data, data(:,1)];
angles = linspace(0, 2*pi, nScen+1);

```



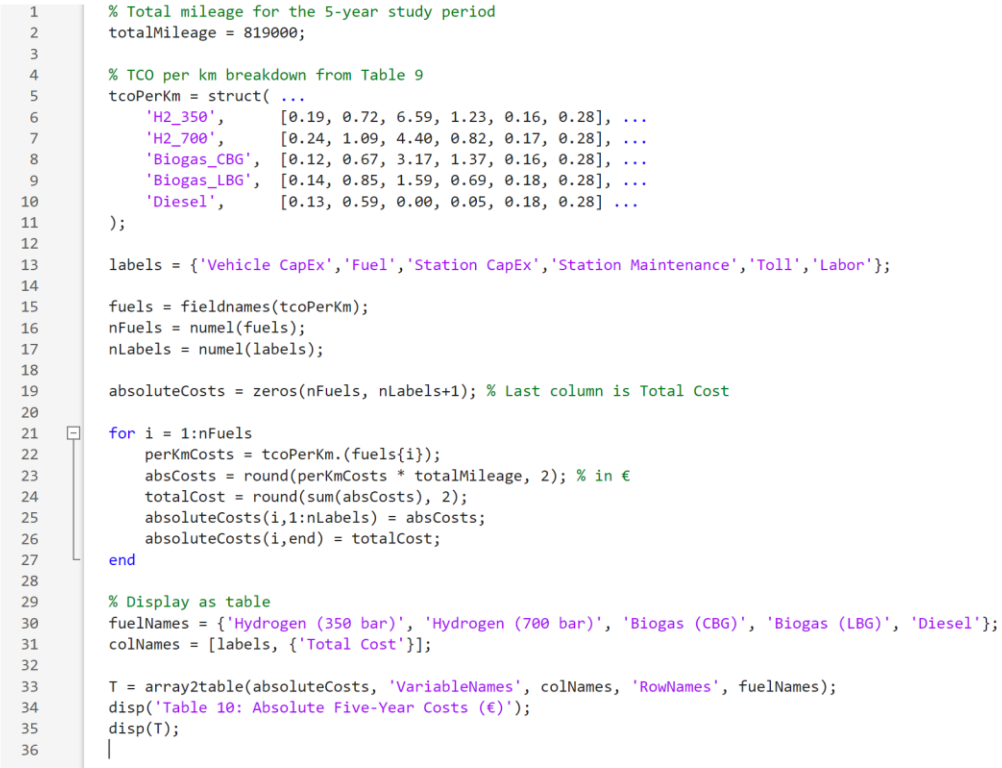
```matlab
% Plot
figure;
ax = polaraxes;
hold(ax,'on');
% ylim()
ax.ThetaTick     = rad2deg(angles(1:end-1));
ax.ThetaTickLabel= scenarios;
ax.ThetaLim      = [0 360];
ax.RLimMode      = 'auto';
title('Radar Chart of TCO/km Sensitivity analysis');

colors = lines(numel(fuelTypes));
for i = 1:numel(fuelTypes)
    polarplot(ax, angles, data(i,:), '-o', ...
        'LineWidth',1.5, 'Color',colors(i,:));
end

legend(fuelTypes,'Location','eastoutside');
hold(ax,'off');

```

Appendix 7. Fuel energy consumption comparison in MJ/km, MATLAB code



```
% 1. Define fuel consumption rates
% -------------------------------
cons_H2_700   = 9.5 / 100;      % [kg/km] Hydrogen 700 bar
cons_H2_350   = 7.75 / 100;     % [kg/km] Hydrogen 350 bar
cons_biogas   = 57 / 100;       % [m^3/km] Biogas
cons_diesel   = 43 / 100;       % [L/km] Diesel

% 2. Define Lower Heating Values
LHV_H2     = 120;   % MJ/kg
LHV_biogas = 22;    % MJ/m^3
LHV_diesel = 37;    % MJ/L

% 3. Calculate energy consumption (MJ/km)
energy_H2_700   = cons_H2_700   * LHV_H2;
energy_H2_350   = cons_H2_350   * LHV_H2;
energy_biogas   = cons_biogas   * LHV_biogas;
energy_diesel   = cons_diesel   * LHV_diesel;

% 4. Create bar chart
energy_vals = [energy_H2_700, energy_H2_350, energy_biogas, energy_diesel];
fuel_labels = {'H_2,700', 'H_2,350 bar', 'Biogas', 'Diesel'};

figure('Color', 'white');
bar(energy_vals, 'FaceColor', [0.3, 0.6, 0.9]);
set(gca, 'XTickLabel', fuel_labels, 'FontSize', 12);
xlabel('Fuel Type', 'FontSize', 12);
ylabel('Energy Consumption (MJ/km)', 'FontSize', 12);
title('Fuel Energy Consumption Comparison (MJ/km)', 'FontSize', 14);
grid on;

% Display values on bars
for i = 1:length(energy_vals)
    text(i, energy_vals(i), ...
        sprintf('%.2f', energy_vals(i)), ...
        'HorizontalAlignment', 'center', ...
        'VerticalAlignment', 'bottom', ...
        'FontSize', 12);
end

% 5. Print to command window
fprintf('Hydrogen (700 bar): %.2f MJ/km\n', energy_H2_700);
fprintf('Hydrogen (350 bar): %.2f MJ/km\n', energy_H2_350);
fprintf('Biogas:             %.2f MJ/km\n', energy_biogas);
fprintf('Diesel:             %.2f MJ/km\n', energy_diesel);

```

Appendix 8. Absolute five-year costs for each fuel type, MATLAB code



```matlab
% Total mileage for the 5-year study period
totalMileage = 819000;

% TCO per km breakdown from Table 9
tcoPerKm = struct( ...
    'H2_350',     [0.19, 0.72, 6.59, 1.23, 0.16, 0.28], ...
    'H2_700',     [0.24, 1.09, 4.40, 0.82, 0.17, 0.28], ...
    'Biogas_CBG', [0.12, 0.67, 3.17, 1.37, 0.16, 0.28], ...
    'Biogas_LBG', [0.14, 0.85, 1.59, 0.69, 0.18, 0.28], ...
    'Diesel',     [0.13, 0.59, 0.00, 0.05, 0.18, 0.28] ...
);

labels = {'Vehicle CapEx','Fuel','Station CapEx','Station Maintenance','Toll','Labor'};

fuels = fieldnames(tcoPerKm);
nFuels = numel(fuels);
nLabels = numel(labels);

absoluteCosts = zeros(nFuels, nLabels+1); % Last column is Total Cost

for i = 1:nFuels
    perKmCosts = tcoPerKm.(fuels{i});
    absCosts = round(perKmCosts * totalMileage, 2); % in €
    totalCost = round(sum(absCosts), 2);
    absoluteCosts(i,1:nLabels) = absCosts;
    absoluteCosts(i,end) = totalCost;
end

% Display as table
fuelNames = {'Hydrogen (350 bar)', 'Hydrogen (700 bar)', 'Biogas (CBG)', 'Biogas (LBG)', 'Diesel'};
colNames = [labels, {'Total Cost'}];

T = array2table(absoluteCosts, 'VariableNames', colNames, 'RowNames', fuelNames);
disp('Table 10: Absolute Five-Year Costs (€)');
disp(T);
```