RELATIVE PRICE AND DEMAND OUTLOOK BETWEEN DIESEL, HYDROTREATED VEGETABLE OIL AND LIQUEFIED BIOGAS UNDER UNCERTAINTY IN FUEL PRICING COMPONENTS

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ABSTRACT

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Relative price and demand outlook between diesel, hydrotreated vegetable oil and liquefied biogas under uncertainty in fuel price components

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Keywords: Diesel, hydrotreated vegetable oil, liquefied biogas, emissions trading system, Geometric Brownian motion, Monte Carlo simulation, sensitivity analysis

This thesis examines the relative price and demand outlook of diesel, hydrotreated vegetable oil (HVO) and liquefied biogas (LBG) in Finnish road transport under uncertainty in fuel price components. The methodology combines Geometric Brownian motion and Monte Carlo simulation to model uncertain future price paths for each fuel. The simulated prices are linked to demand development through an elasticity of demand model.

The results indicate that retail prices increase for all three fuels during the examination period. Relative price development is examined through energy content, in megawatt hours, where LBG remains the cheapest and HVO remains the most expensive. Demand for diesel and HVO decreases in the model, whereas LBG increases. The sensitivity analysis shows that the tax-free base price component is the biggest driver of final price uncertainty for all three fuels.

The findings suggest that future fuel competitiveness should be evaluated through a combination of market price uncertainty and regulatory restrictions. The model provides a framework, where fuel price assumptions are easily adjustable. To gain more accurate price and demand projections, future research should utilize more advanced stochastic processes that consider sudden market shocks and irregular price patterns.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

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Suhteellinen hinta- ja kysyntänäkymä dieselin, vetykäsitellyn kasviöljyn ja nesteytetyn biokaasun välillä epävarmojen hintakomponenttien vallitessa

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Tämä tutkielma tarkastelee dieselin, vetykäsitellyn kasviöljyn (HVO) ja nesteytetyn biokaasun (LBG) suhteellista hinta- ja kysyntänäkymää Suomen tieliikenteessä tilanteessa, jossa polttoaineiden hintakomponentteihin liittyy epävarmuutta. Menetelmä yhdistää Geometrisen Brownin liikkeen ja Monte Carlo -simulaation kunkin polttoaineen epävarmojen tulevien hintapolkujen mallintamiseksi. Simuloidut hinnat yhdistetään kysynnän kehitykseen kysynnän hintajoustomallin avulla.

Tulokset osoittavat, että kaikkien kolmen polttoaineen vähittäishinnat nousevat tarkastelujakson aikana. Suhteellista hintakehitystä tarkastellaan energiasisällön perusteella megawattitunteina, jolloin LBG pysyy edullisimpana ja HVO kalleimpana vaihtoehtona. Mallissa dieselin ja HVO:n kysyntä laskee, kun taas LBG:n kysyntä kasvaa. Herkkyysanalyysi osoittaa, että veroton perushintakomponentti on kaikkien kolmen polttoaineen lopulliseen hintaepävarmuuteen eniten vaikuttava tekijä.

Tulokset viittaavat siihen, että polttoaineiden tulevaa kilpailukykyä tulisi arvioida markkinahintojen epävarmuuden ja sääntelyyn liittyvien rajoitteiden yhdistelmänä. Malli tarjoaa viitekehyksen, jossa polttoaineiden hintaoletuksia voidaan helposti muuttaa. Tarkempien hinta- ja kysyntäennusteiden saavuttamiseksi tulevassa tutkimuksessa tulisi hyödyntää kehittyneempiä stokastisia prosesseja, jotka ottavat huomioon äkilliset markkinashokit ja epäsäännölliset hintavaihtelut.

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They say time goes by quicker as you get older, and this has certainly been the case. The past six years at LUT have included so many new friends and adventures that I was not prepared for. Above all, I want to thank my dear friends for all the shared experiences, and my family for the unconditional love and support they have always offered.

Turku, 27.5.2026

Teemu Turunen

ABBREVIATIONS

EU	European Union
ETS1	Emissions Trading System implemented in 2005
ETS2	Emissions Trading System starting in 2028
ESR	Effort Sharing Regulation
MSR	Market Stability Reserve
HVO	Hydrotreated Vegetable Oil
LBG	Liquefied Biogas
RED	Renewable Energy Directive
ULSD	Ultra-low sulphur diesel
TTF	Title Transfer Facility
GBM	Geometric Brownian motion
SimDec	Simulation decomposition

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DECLARATIONS

AI usage

The author of the thesis, Teemu Turunen, used the following AI-tools during the preparation of the thesis:

1. Chat GPT
    a. Purpose of use:
        i. Literature sources
        ii. Thesis structuring
    b. Explanation of the use of the tool: Asking Chat GPT, what existing literature there already is on the topics and methodologies relevant to this thesis. Requesting ideas and help on how to structure the thesis.
2. Consensus AI
    a. Purpose of use: Scientific literature sources
    b. Explanation of the use of the tool: Asking Consensus AI, what existing scientific literature there already is on the topics and methodologies relevant to this thesis.

Responsibility

The author, Teemu Turunen, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI tools.

1 Introduction

1.1 Background

An overwhelming scientific research consensus indicates a strong connection between human activities and the rapid change in climate across the world of which we have begun to witness the consequences during the past years in more extreme and frequent weather phenomena (Lynas et al. 2021). Public demonstrations arising from climate activism are becoming increasingly daring and supranational institutions such as the United Nations and the European Union are introducing policy frameworks with increasingly ambitious targets to accelerate the transition toward low-carbon solutions.

The UN Climate Change Conference in Paris in 2015 (COP21) resulted in an agreement that brought countries together in a commitment to limit global warming to 1,5 degrees Celsius compared to pre-industrial levels. Reaching this goal requires each country to utilize the best science-based knowledge available to target investments in economically and socially efficient fields. (United Nations Climate Change 2025) For member states of the European Union, legislation and structure to incentivize achieving this common goal have been defined in the European Climate Law. (European Parliament and Council 2021)

The EU has agreed on an objective of 55% reduction in greenhouse gas emissions by 2030 and a longer term objective of reaching carbon neutrality by 2050 in its package “Fit for 55”, which is compiled of several measures for different sectors of society in the effort to make cleaner technologies more accessible and economically competitive while supporting employment and ensuring sustainable social policies. The prominent instruments of this package consist of carbon pricing mechanisms such as the EU emissions trading system (EU ETS), stricter regulations on emission standards for vehicles and buildings, as well as social support mechanisms, which enable low-income households and small businesses to invest in more sustainable energy and heating solutions. (European Commission 2021)

As the transport sector is one of the major sources of greenhouse gas emissions in the European Union currently, developing and introducing new regulatory mechanisms such as

extending emission trading system as well as tightening renewable fuel obligations are key measures in the EU's strive to reduce its emissions (European Environment Agency 2024).

1.2 Industry problem and research gap

The dynamics of global fuel markets are being altered by an evolving regulatory environment. Traditional fossil road transport fuels are increasingly subject to carbon pricing and tighter taxation, while the use of renewable alternatives such as hydrotreated vegetable oil (HVO) and liquefied biogas (LBG) are incentivised through direct taxation incentives as well as blending mandates.

The fuel markets are inherently uncertain. As the global energy supply chains are so optimized and critical for modern economies, they are very sensitive to abrupt changes. Recent events, including COVID-19, the energy crisis in Europe and geopolitical conflicts in the Middle ast, have highlighted the volatility of energy markets.

For energy companies operating under such unpredictability, understanding the possible future developments of fuel prices and demand is highly important for strategic decision making. An ability to estimate and analyse the impacts between market driven price dynamics and policy-induced costs can provide crucial insight for the future.

Existing literature already examines many individual aspects of this problem. When considering uncertainty in parameters, stochastic techniques such as Geometric Brownian motion and Monte Carlo simulation are widely used to model price dynamics in commodity markets. Similarly, price elasticity of fuel demand and the impact of taxation on consumer behaviour has been extensively studied.

Previous literature lacks integrated approaches, where stochastic price development, policy-driven cost components and demand responses across alternative fuels are considered. This research gap is particularly relevant in the context of road transport in Finland, where freight is being transported mostly by trucks. As road transport can use multiple energy sources, policy decisions play a key role in shaping market prices.

Research questions:

1. How is the price relativity of diesel, HVO and LBG expected to develop under uncertainty in fuel price components?
2. What is the impact of fuel price on demand?

1.3 Objective and significance of the thesis

This thesis complements existing literature by combining stochastic price modelling with policy-driven price components and demand elasticity into a single analytical framework. Geometric Brownian motion and Monte Carlo simulation is used to capture uncertainty in both market prices and policy instruments. The objective is to provide a comparative analysis on how price dynamics differ between competing fuel types and how that is reflected in demand. In a transition to greener energy solutions, this thesis offers a more comprehensive understanding of fuel market evolution.

This thesis is completed as a commission for St1, a Finnish energy company, which is primarily known for its fuel retail business in the Nordics. In addition to tradition fossil fuels, St1 has made extensive investments into renewable energy solutions such as bioethanol, renewable diesel oil, sustainable aviation fuel (SAF), biogas and wind energy.

From a practical perspective, the results provide insight for energy companies operating in highly regulated markets, where price volatility and policy developments steer strategic decision making. The methodology and calculation tools used here are designed to offer an accessible template to adjust parameters and back-track calculation logic if an energy company chooses to use the model.

1.3.1 Limitations

Despite St1 having extensive business in Sweden and Norway in addition to Finland and due to national differences in regulation, to keep the scope of the thesis reasonable, the focus is on the road transport sector in Finland from a comparative price and demand perspective of three major heavy transport fuels, diesel, HVO and LBG.

As ETS2 will come into force in 2028 and currently there being only a handful of EUA2 futures in the market, making it very illiquid, it should be acknowledged that the ETS2 effect on the results is highly speculative and should be treated as such. Additionally, the results from the whole model should be considered more as a high-level approximation. Once historical price data is available, model parameters can easily be adjusted accordingly, and the accuracy of forecast should improve.

Methodology wise, a relevant limitation comes from Geometric Brownian motion as it does not explicitly capture sudden market shocks or irregular price patterns that may result from geopolitical crises or pandemics but models a continuous stochastic price development. More advanced stochastic processes such as jump diffusion models may reflect these dynamics more accurately. Hence, the model used in this thesis should be considered more as a tool for estimating general price development trends rather than precise market reactions.

1.4 Structure

The next chapter will explain essential concepts to provide some background information for the following sections of the thesis. After the theoretical background, the applied data and methodologies are presented. The data and methodology sections are followed by an analysis of the results, which will then be concluded with the overall findings and suggestions for further research.

2 Theoretical background

First this chapter will explain the fuel types examined in this thesis and will then define the main concepts in more detail to provide a better understanding of the components that are relevant to the formation of fuel retail price.

2.1 Diesel and HVO

Many light vehicles and vast majority of heavy transport on the Finnish roads use diesel fuel as their source of energy due to diesel's reliability and fuel efficiency gains over gasoline (Biscontini 2024). Commonly known as diesel, it is a distillate fuel oil refined from crude oil and biomass materials (EIA 2022). Despite having many performance advantages, crude oil derived diesel is particularly harmful to the environment, even when less toxic low sulphur diesel fuel is used (Biscontini 2024).

Hydrotreated vegetable oil, also known as HVO, is a diesel-like fuel that has been refined from 100% renewable raw materials. This product can also be referred to as HVO100. Common raw materials are used cooking oil and animal fat waste. Compared to regular diesel, HVO has performance and climate related advantages. HVO does not draw moisture in and is therefore easier to store for longer periods of time and has a higher cetane number than fossil diesel, leading to a more efficient combustion event in the engine. Another performance advantage comes from a cost efficiency perspective. In a policy environment that assigns a blending mandate, such as Finland, HVO can be blended directly with regular diesel, which means that private motorists and especially logistics companies do not have to update their truck fleet as HVO is a perfect substitute for diesel. (Neste Oyj 2025)

Greenhouse gas (GHG) emissions from fuels are calculated based on the life cycle emissions of the product, which includes all processes from extraction to refining as well as emissions from logistics and the use of the end product. HVO that fulfils European specifications requirements, reduces GHG emissions by up to 90% compared to fossil diesel. (Neste Oyj 2025)

Figure 1 illustrates the production process of HVO, from feedstock to different fuels. As is evident, this process produces multiple different products, which can be utilized for various purposes. The product examined in this thesis is renewable diesel.

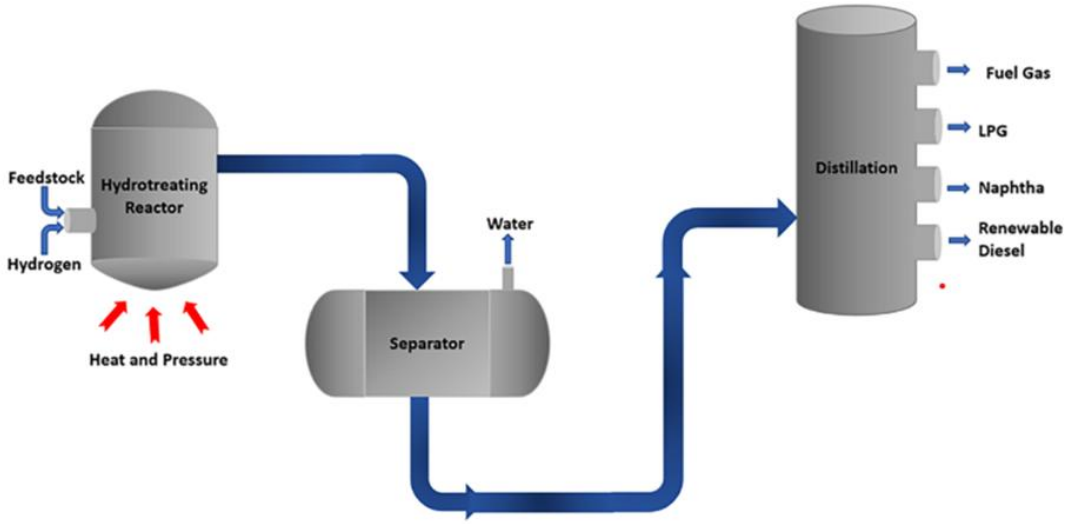

Figure 1: Renewable diesel production process (Baker Institute 2025)

2.2 Biogas and Biomethane

The general discussion regarding gaseous fuels usually refers only to natural gas and biogas, its renewable substitute, perhaps unintentionally forgetting biomethane. For the sake of clarification, it is useful to determine the distinctive attributes of different gases, which are ultimately very common sources of energy all around the world.

Similar to HVO, biogas is produced from biomass, however, raw materials consist of wastewater sludge, animal manure and crop residues and other waste and residue materials. Biogas is a result of the raw materials going through an anaerobic digestion process, which results in a gas with low methane content that can then be used for district heating, cooking and electricity production. Natural gas is a fossil energy source with high methane content,

which is why it can be used as a fuel to power cars, trucks and sea vessels in addition to the formerly mentioned use cases. (International Energy Agency 2025)

Biomethane is an upgraded version of biogas, where excess oxygen and other impurities from biogas are removed to end up with “renewable natural gas”. Biomethane is a direct substitute to natural gas and those can be blended in any ratio. Figure 2 displays the life cycle of biogas and biomethane. (International Energy Agency 2025).

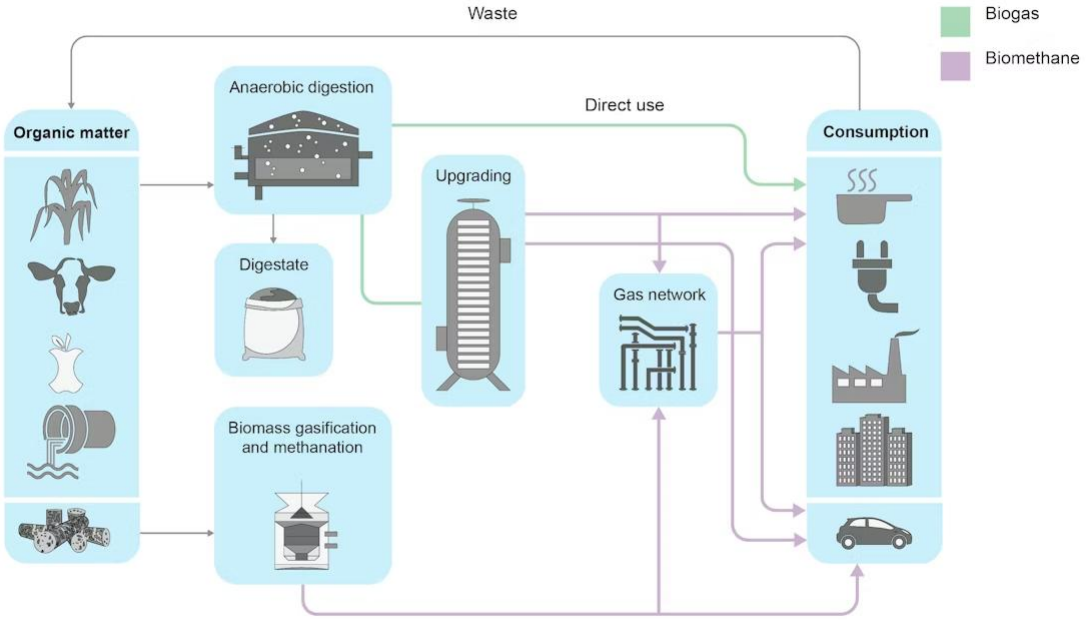

Figure 2: Life cycle of LBG and biomethane. (International Energy Agency 2025)

The upgraded biomethane product can then be compressed and liquefied depending on the use case. Compressed biogas is referred to as CBG and liquefied biogas as LBG. LBG is the fuel product which is used by heavy transport vehicles, and it is the main form of biomethane sold into road transport in Finland. Therefore, all calculations and logic in this thesis is based on LBG specifications.

2.3 Emissions trading system

To achieve its ambitious, yet necessary, emissions reduction goals, the EU has had to tighten existing sustainability requirements as well as introduce new measures. The current emissions trading system has excluded road transport, agriculture, buildings and smaller industries. Emissions from these are placed under the Effort Sharing Regulation (ESR), by which each member state has been assigned an emissions target to achieve for 2030 (European Commission 2023).

Road transport being one of the major sources of emissions in Europe, as a key method, the EU has decided to introduce a new emissions trading system, known as ETS2, to cover road transport as well as buildings and smaller industry not covered by the existing ETS, which the European Commission had already specified in their "Fit for 55" package (European Commission 2021). However, the emissions targets specified in the ESR will remain active despite the application of ETS2. Initially, this extension was suggested to be implemented in 2026, but the timetable was pushed forward slightly and was due to start in 2027. In November 2025, the EU revised the implementation to be postponed once again to 2028. (European Commission 2025b)

To complement ETS2 and further lever the emission reduction goals, the Renewable Energy Directive (RED) was amended to its third iteration, now known as RED3, to increase renewable energy source obligations. According to the new requirements, 29% of energy used in the transport sector should come from renewable sources. (European Parliament & Council 2023b) Every member state will implement this regulation on a national level. In Finland, this is known as the blending mandate, which regulates fuel distributors on the share of renewable fuels that must be blended in with fossil fuels.

The regulatory framework for ETS2 was concluded in 2023 and is a "cap-and-trade" carbon allowance trading system similar to the first emissions trading system (ETS1). A certain amount of emission allowances (EUA) will be allocated for auctioning each year, which will be equivalent to the cap, and each allowance covers one tonne of CO_2. Companies are able to save bought allowances for later use but cannot borrow allowances from the future.

A key distinction between the new ETS2 and the current ETS1, is its focus on upstream emissions, now subjecting fuel distributors under the carbon allowance obligations. With the

implementation of ETS2, emissions from buildings and mobility are intended to decrease around 42% compared to 2005 levels. (European Commission 2023) Additionally, all allowances under ETS2 will be auctioned (European Parliament & Council, 2025). In ETS1, between years 2021 and 2030, 57% of new allowances are released into the markets through auctions while the rest are allocated for free to promote environmentally friendly technologies and to prevent carbon leakage. 90% of the to-be-auctioned allowances are distributed between Member States based on their historical emissions. The remaining 10% is distributed between 16 Member States for solidarity purposes. The revenues that Member States collect from the auctions, go to national budgets as well as the Innovation Fund, Modernisation Fund and as of 2026, the Social Climate Fund (European Commission 2025c)

An integral part of ETS2 is the market stability reserve (MSR) as it was already in ETS1 as well, however ETS2 will have its own separate reserve. The MSR holds an initial stock of 600 million allowances, which is intended to function as a price control mechanism that will issue extra allowances and withdraw allowances from the market when certain conditions are triggered. The mechanism can be triggered based on quantity of allowances in the market or the market price of allowances. The quantity-based mechanism aims for an excess of 210 – 440 million allowances in circulation above the emission cap. If the 440 Mt CO2 is exceeded, the MSR will remove allowances from the market and if the market is short of 210 Mt CO2, new allowances will be released. In the price-based mechanism, new allowances will be released in case the market price of allowances rise too rapidly or if the price allowances exceed 45€ for two consecutive months, however, this mechanism can be triggered only once in a 12-month period. If necessary, the Commission has the option to cancel this restriction through a separate decision. (European Parliament & Council 2023a)

As of beginning of January 2026, the ETS2 futures are already at around 70-80€, which would already trigger the MSR if the ETS2 would come into force now. The possible increase in allowances to market can also be problematic for achieving emissions reductions targets on EU level, which will put pressure on individual member states to tighten their emission regulation. As this is more difficult for poorer members, EU's effort sharing regulation will most likely distribute this burden on countries with higher ESR targets.

2.4 Blending mandate

In Finland, like in other member states, the blending mandate is a national implementation of the targets set in the RED into Finnish law, more specifically, Jakeluvelvoitelaki 446/2007 ("Blending mandate law"). The blending mandate law obligates all companies that distribute at least nine million litres of road transport liquid fuels or 9 gigawatt hours of gaseous fuels and dictates the share renewable fuels to be blended in with fossil fuels for each year. In 2025, the overall level was set at 16,5%, which is set to gradually increase until 2030, whereafter, the level is set to remain at 34%. (Energiavirasto 2025)

The blending mandate is subdivided into four components that specify the minimum amounts of different bioproduct requirements. In 2025, three percentage points of the blending mandate must be fulfilled with advanced biofuels. From 2028 onwards, fuel distributors will be obligated to supply RFNBOs (Renewable Fuels of Non-Biological Origin) by 1,5 percentage points, which is also set increase in coming years. RFNBOs are synthetic fuels produced out of hydrogen. (Energiavirasto 2025) Figure 3 illustrates the development of the blending mandate levels in 2025-2030.

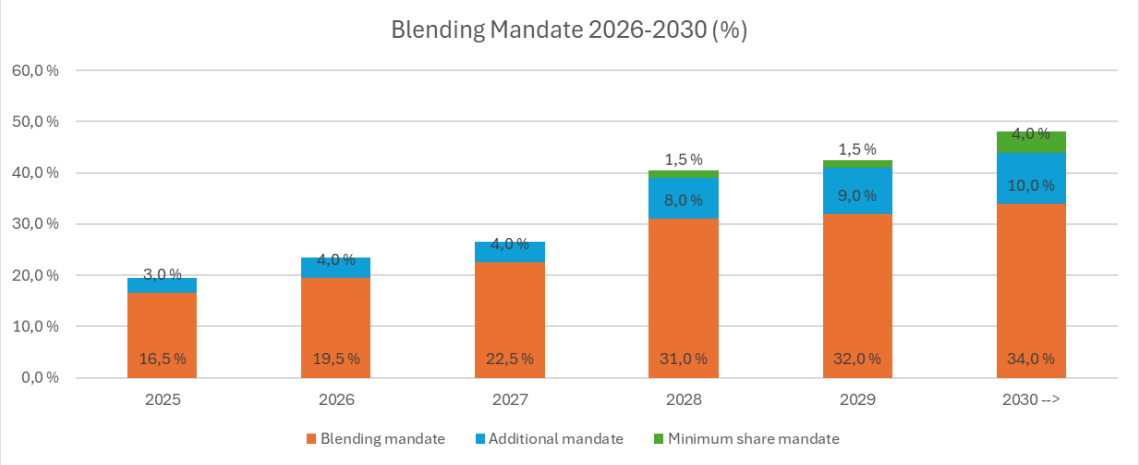

Figure 3: Blending mandate levels in Finland 2025-2030 (Energiavirasto, 2025)

To be considered as an advanced fuel in the EU, the raw materials, more specifically referred to as feedstocks, must be listed in Part A of Annex IX in RED2. Annex IX-A feedstocks are mainly waste and residue derived materials from industries, agriculture and general waste

management. (European Commission 2025a) In the Finnish blending mandate starting from 2028, RFNBOs can also be used to fulfil the requirement of advanced fuels (Energiavirasto 2025)

2.5 Fuel taxation

To make fuel price easier to understand, it should be decomposed to more accurately defined components. For the sake of this thesis, the first component is referred to as just the "tax-free price", which is a bundle consisting of the costs of sourcing, refining and logistics as well as other distributor related costs and margins. Value-added tax, carbon taxes and other tax-like policy-induced surcharges, such as ETS2, are added on top to form the retail price.

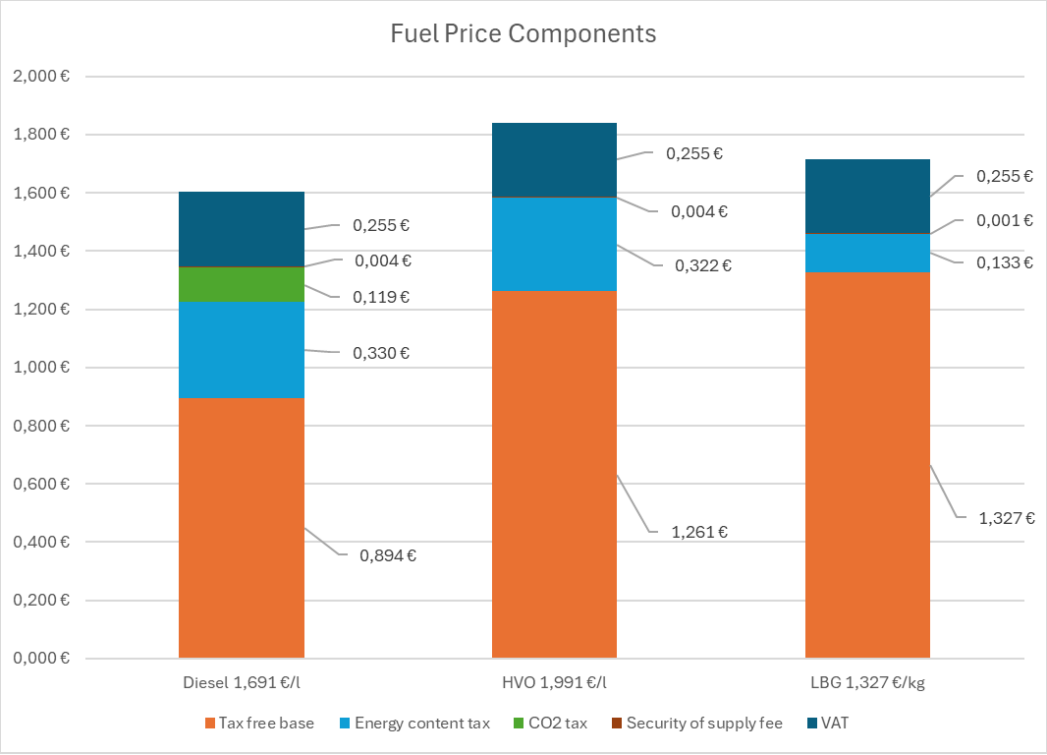

Figure 4: Fuel price components per fuel type

As is evident from Figure 4, taxes have a significant impact on the final price of fuel in Finland. Apart from value-added tax, which is currently 25,5% in Finland, the tax components are defined as euros per litre. These components are the energy content tax, carbon dioxide tax and the strategic stock fee. The advantage of Annex IX-A fuels is their exemption from carbon dioxide tax. Other renewable feedstocks, such as Annex IX-B that can be used for example in HVO, have a lower CO2 tax than fossil diesel but not zero. (Verohallinto 2025) In this thesis 100% HVO is calculated as Annex IX-A and HVO blended to diesel is considered as Annex IX-B.

3 Literature review

This chapter compiles relevant literature from the past in relation to the topic and objectives of the thesis, providing support from earlier applications of similar methodologies as well as insight on what has already been researched.

3.1 Forecasting energy prices under uncertainty

The academic field of finance has established the Geometric Brownian motion in combination with Monte Carlo simulation as a good way to model stochastic price paths of assets and commodities, and its use has been most prevalent in equity market related research. For instance, Xiang et al. (2021) combined Geometric Brownian motion and Monte Carlo simulation with a thousand simulations runs to create future price paths to gauge its suitability as a tool for stock traders. Their findings suggest that increasing the number simulation runs improves forecast accuracy and utilizing 1 000 to 10 000 runs is optimal, as increasing the number of iterations excessively reduces its marginal benefit (Xiang et al. 2021). Similarly, Sinha (2024) models daily and weekly price paths for indices such as the DJIA, NASDAQ and S&P 500, concluding that a relatively low number of iterations can be enough to provide sufficiently reliable forecasts. These studies indicate that GBM and Monte Carlo simulation provide an efficient way to produce reasonably accurate forecasts, even at a low number of simulations.

Compared to equity markets, the suitability of GBM is not as self-evident in commodity markets, where price dynamics are different. Mosiño & Moreno-Okuno (2018) studied fossil fuel prices and compared Geometric Brownian motion and variance-gamma process with findings suggesting that GBM lacks the ability to capture drastic price swings, which is typical in the fossil fuel markets. This limitation is also supported by Dehghani et al. (2025), who prove that without any extra factors, GBM is reliable in the short-term but loses accuracy in the long-term. Both aforementioned studies are somewhat of a continuum to earlier research by Pindyck (1999), which concluded that stochasticity is a key attribute in commodity price development to represent up- and downward spikes.

To overcome some of the weaknesses of Geometric Brownian motion, alternative solutions or extensions of GBM have been proposed in the energy markets. Liu et al. (2024) combined GBM with a stochastic partial differential equation instead of Monte Carlo simulation. Previously, Cortazar and Schwartz (2003) had used a three-factor stochastic model, which combines GBM-comparable dynamics with some additional factors to introduce other sources of uncertainty that improve the model to reflect real-world conditions in commodity pricing. While these are advanced application of GBM, Nwafor & Oyedele (2017) demonstrate that a simple GBM model can improve forecasting accuracy substantially, when it is an improvement from previous modelling methods, for instance, compared to the naïve forecasting method commonly used in developing countries with large energy exports.

The Geometric Brownian motion combined with Monte Carlo simulation has been utilized in the context of carbon markets as well, which incorporates different dynamics than the aforementioned markets. Lee & Ham (2023) used GBM to test its applicability to model price paths for the first EU emissions trading system by utilizing historical data and simulating future price trajectories. Their findings suggest that the model output is highly sensitive to the estimation window and the parameters. Shorter estimation windows tend to create more volatile price fluctuations, leading to higher forecasts. The authors note that carbon markets are also largely affected by geopolitics and governmental policies, which cannot be captured by stochastic process alone, and highlights a key limitation of GBM. (Lee & Ham 2023)

Overall, previous literature on the use of Geometric Brownian motion and Monte Carlo simulation supports their usefulness for modelling general baseline forecasts in the financial, commodity and carbon markets. The strengths of this method are demonstrated by its simplicity and efficiency in providing relatively accurate approximations of future price paths in the short term especially. However, the stumbling block of GBM is parameter estimation, which is evident from the existing literature, and limits the method's ability to reflect real-world behaviour. This limitation is relevant in energy markets, where fuel prices are increasingly influenced by policy-driven incentives and uncertainty.

3.2 Demand response to fuel price changes

Energy consumption behaviour is frequently talked about in the media, particularly in times of crisis, and when such a phenomenon is combined with economics, price elasticity is a key concept. Research on price elasticity of fuel demand has been conducted for decades, and early studies by Graham & Glaister (2004) and Goodwin et al. (2004) conclude a rather inelastic demand in the short-term of just -0,25, meaning that consumers are not changing their consumption behaviour much in the short-term. Elasticities ranged between -0.6 and -0.7 in the long-term, indicating a shift that can be driven by the availability of more economically feasible technologies. Later research by Brons et al. (2008) decomposed price elasticity to multiple factors with their own elasticity ranges, ultimately producing similar elasticity figures as previous research. Dahl's (2012) study on price elasticity drilled down to country level elasticities for gasoline and diesel separately, further supporting an inelastic conclusion, particularly in Finland's case.

A Norwegian study by Fridstrøm & Østli (2021) highlighted that fuel price elasticity estimates can be highly determined by available substitution possibilities, which is a direct consequence of technological advancements. According to their findings, elasticity factor increases, when new alternative propulsion technologies are available. Despite their relatively high elasticity factor for traditional vehicles of approximately 1, elasticity among electric and hybrid-electric vehicles displays even greater responsiveness. Additionally, increases in fossil-based fuel prices directly increases demand for vehicles of substitutionary energy sources. (Fridstrøm & Østli 2021)

As is the case for the older papers, the base data for price elasticity calculations have been quite old, which has lost relevance in relation to the modern world. Before the 2010s, fighting climate change was not prioritized as highly in the political agenda as it has been since the Paris climate agreement. ETS2 is an example of a market mechanism that should increase the price of liquid fossil fuels and therefore incentivise switching to more sustainable energy solutions. As electrification in road transport is increasing and the technology is becoming a more viable option to consumers, this structural shift implies that elasticity estimates derived from earlier papers possibly underestimate responsiveness, which is also an assessment supported by Seppänen et al. (2022), stating that this is most likely the reason for higher elasticity factors encountered in recent studies. Additionally, they highlight that elasticity

estimates derived from tax-induced price changes are often higher than those springing from market price fluctuations such as spikes in crude oil price. (Seppänen et al. 2022)

A major contributing factor to the size of elasticity is influenced by how the price changes appear to the customers. The impact of taxes in demand can also be referred to as tax salience in demand, meaning that consumption behaviour is more likely to change when the increase in price is due to taxes is made more visible. Chetty (2009) examines this in the retail sector, showing that tax inclusive price tags decrease demand by eight percent compared to adding the tax at the register. Finkelstein's (2009) findings on electronic road toll systems supports a statement that reduced tax salience reduces sensitivity to price changes as perceived costs are lower. Therefore, a lower price transparency allows for higher effective prices and displays that elasticities are greatly affected by behavioural factors.

Recently, a study specific to Finland was conducted by Harju et al. (2025), providing further insight on how elasticity also varies geographically. In 2012, a fuel taxation reform was passed, where the taxation of diesel was increased quite substantially relative to gasoline, 12 cents per litre compared to three cents per litre. According to the authors, the impact on price elasticity as a consequence of tax adjustments could be as high as -0,7 in rural areas and -1 in urban areas, which is partly explained by the availability of public transport and other commuting alternatives in the urban areas. (Harju et al. 2025)

As Finland is a relatively large, scarcely populated country, the price elasticity effect is limited due to the extensive necessity for cars in rural areas, where long distances to everyday destinations, such as grocery stores, schools and workplaces are common, and public transportation is practically absent. Increasing fuel prices through taxation in an attempt to increase government revenue or incentivise switching to more sustainable and expensive vehicle types can be politically difficult as the population residing outside the biggest cities can be financially disproportionately affected.

The challenge is not only distinctive to Finland, but a similar perspective is also shared across Europe and the world in general. While economists widely agree that carbon taxes are an efficient way to incentivize the green transition over a subsidy or tax rebate approach, multiple studies have shown how policymakers' decisions are affected by the public's preference for subsidies over tax-like solutions. Some voters are concerned about the initial regressive nature of carbon taxes without any counterbalancing measures, whereas for some,

carbon tax is seen more as a ploy to increase government revenues without any real-world effects on high carbon behaviour. (Carattini et al. 2018)

Consumer responsiveness to fuel taxation is also affected by how the taxes are transferred to the end-user at the fuel pumps, which ultimately determines the effectiveness of taxation. In an earlier paper Harju et al. (2022) found that the 2012 tax reform was estimated to be passed through with a factor of approximately 0,8. Their outcome is contradictory to previous literature globally, as many studies have been done in the US, where inadequate public transportation systems do not provide sufficient substitution possibilities. (Harju et al. 2022)

Overall, historic literature indicates an inelastic price, especially in the short term. More recent studies have found price elasticity to be multi-dimensional, where consumer behaviour is driven by other factors in addition to price alone. Consumer responsiveness is seen to increase with the increasing availability of substitutionary options, which particularly in the road transport sector has been driven by the rise in electric vehicles and the possible savings they offer in relation to traditional vehicles. However, demand responses are also affected by tax salience and regional infrastructure, further cementing that price elasticity is a very dynamic parameter, which cannot be generalised, but rather defined based on the factors relevant to the examined market. Additionally, changing market and policy conditions can quickly lead to inaccurate or outdated research results.

3.3 Research gap

Previous literature has studied stochastic price modelling, commodity and carbon markets, as well as price elasticity of demand extensively. Existing studies support the usefulness of Geometric Brownian motion and Monte Carlo simulation in modelling price paths reflecting uncertainty. Literature on elasticity suggests that consumer responsiveness to fuel prices is affected by substitution possibilities, taxation, infrastructure and other behavioural factors.

However, these pieces of literature remain disconnected as previous research has typically focused either on modelling price dynamics in financial, commodity or carbon markets, or on fuel demand elasticity separately. Current research is lacking comparative analysis on

how uncertainty in fuel price dynamics, policy mechanisms and demand responsiveness interact simultaneously across competing transport fuels.

4 Data

Data used in this thesis includes publicly available data from Finnish and European institutions as well as private market research institutions and market spot quote providers. In June 2024, the Finnish Prime Minister's Office published a research report written by Koljonen et al. (2024) on the Finnish energy and climate actions, called *Perusskenaariot energia- ja ilmastotoimien kokonaisuudelle kohti päästöttömyyttä*, also known as PEIKKO, an abbreviation, which will be used in this thesis hereafter. PEIKKO was a collaborative effort between VTT Technical Research Centre of Finland, The Finnish Environment Institute (SYKE) and The Natural Resources Institute Finland (LUKE) to examine and assess Finland's climate actions that were put into place to achieve its 2035 carbon neutrality goal. The report evaluates the sufficiency of the existing actions using "low", "base" and "high" scenarios to estimate the development of greenhouse gas emissions in Finland. All the scenarios used the same climate measures but differed in their assumptions on how the operating environment is assumed to change, therefore impacting the success of sustainable investments and behavioural development in agriculture and transport. (Koljonen et al. 2024) VTT et al. (2024) have published an Excel workbook of the values used in the PEIKKO report, which defines forecasted yearly figures for multiple transport sectors with several levels of granularity, such as energy consumption and emissions from aggregate levels to specific vehicle and fuel types.

As the pricing of ETS 2 is considered in euros per tons of CO2 emissions, and traditional liquid fuels are priced in euros per litre, the price of carbon allowances must be converted accordingly, for which fuel property factors have been retrieved from Statistics Finland. Some background calculations used in the PEIKKO report, such as bio product share per fuel type and energy consumption projections for the next decades, are used as baseline assumptions in this thesis (VTT; Syke & Luke 2024).

In the global energy market, small nations, which import energy are usually "price takers" rather than "price makers", meaning they do not hold market power to dictate price trends. Energy markets can be very volatile and uncertain as has been evident during the last five to six years. A fundamental market price component of diesel in Europe is based on ultra-low sulphur diesel (ULSD), which is quoted in the spot market. The equivalent spot quote for

natural gas in Europe is Title Transfer Facility (TTF). The price of renewable fuels, HVO and LBG in this case, follows the same pricing components as their fossil counterparts, and therefore display similar price trends.

5 Methodology

Predicting the future is a challenge that companies and researchers have been trying to solve for decades with various models and methods, and understandably so. In energy and commodity markets in general, future price development is affected by volatility in the markets, driven by its inherent uncertainty as well as geopolitical instability and regulatory changes. Geometric Brownian motion combined with Monte Carlo simulation has established itself as a suitable approach for modelling stochastic price paths in financial, commodity and carbon markets (Pindyck 1999; Mosiño & Moreno 2018; Lee & Ham 2023).

Therefore, this thesis uses Geometric Brownian motion paired with Monte Carlo simulation to model the future price paths and demand development of three competing road transport fuels in Finland by incorporating uncertainty in key price components. This methodology is chosen to provide an estimation of the general development trends and relative differences between fuel types under uncertainty, rather than seeking to produce an exact forecast.

Since the development of fuel prices is fundamentally uncertain, the modelling method is complemented with a sensitivity analysis that helps examination into how simulation outcomes are influenced by variations in key assumptions. In addition to modelling future price paths, this enables the assessment of model robustness under different input conditions.

5.1 Geometric Brownian motion and Monte Carlo Simulation

The base of the model in this thesis is the Geometric Brownian motion, in which the model's target changes by percentages over time and these changes create a random walk through the examination period. The standard equation for GBM is the following:

$$dx(t) = x(t) * [\mu\, dt + \sigma\, dB(t)] \quad (1)$$

where *x(t)* is the initial value of the instrument, μ is the drift (i.e., percentual change), σ is the volatility and *B(t)* determines the standard Brownian motion. (Stojkoski et al. 2020)

In this thesis, the GBM method is used to model the future price development of each fuel type based on historical data. Furthermore, GBM is applied to the price of EUA 2, which is an addition component to diesel's retail price from 2028 onwards.

To achieve more robust results, the standard GBM model is complimented with a Monte Carlo simulation. Monte Carlo simulation is a term used for a category of stochastic simulations, where randomness is incorporated into the model through distributions in input parameters. A Monte Carlo simulation has a predefined number of simulation runs, where each simulation draws a random set of values from the input parameters. The result of these simulations are the possible outcomes. (Bonate 2001) In combining Geometric Brownian motion and Monte Carlo simulation, GBM is the model within the Monte Carlo simulations that provides the parameter inputs. As Sinha (2024) and Xiang (2021) have noted in previous research that preferably 1 000 to 10 000 simulation runs are an optimal amount, the results in this thesis are calculated using 10 000 simulations per product ensuring repeatability under the defined variable restrictions, which are specified in the following parameters section.

5.1.1 Parameter definition

Similar to investment instruments, the price of EUA 2 is determined in the market by supply and demand. As the ETS 2 will not commence until 2028 and with the low liquidity of the current EUA 2 futures in circulation, the price allowances are still very speculative. Based on calculated estimations provided in existing literature, Lento-Hukkinen (2025) created three scenarios for EUA 2 prices with starting prices of 60€, 100€ and 140€ per tCO2 during the first year. In this thesis, the starting price for year 2028 is set between the low and high scenarios defined by Lento-Hukkinen (2025). For the following years, the price is modelled using Geometric Brownian motion.

According to the Hotelling rule, the growth rate of price equals to the interest rate, when firms under ETS-like emission restrictions are allowed to bank allowances for later use.

(Rubin, 1996) The Hotelling rule has become a standard in research studying these kinds of instruments. Bocklet et al. (2019) decided to use an interest rate of 8%, which approximated the weighted average cost of capital in energy intensive industries. Perhaps the most common discount rate is approximately 5%, which was also used by Pahle et al. (2025) in their analysis of ETS 2's future.

When examining the price development in ETS 1 over the last five years, the average growth rate has been 22% annually with a volatility of 39,5%, however, if only the last four are considered, those numbers decrease to 7,6% and 26,3%. For the first fifteen years of the ETS, the price of one allowance fluctuated between 0€ and 30€, and from roughly 25€ in 2020, the average price was already over 80€ in 2022 and 2023 (Dimitrova 2024). This illustrates the very volatile nature of allowance prices. Considering the Hotelling rule and EUA 1 data, the growth rate chosen for this thesis is aligned, however, the range for volatility has been brought down to slightly more conservative level as is displayed in Table 1.

	Growth rate (drift)	**Volatility**
ETS 1 2022-2025	7,6 %	26,6 %
ETS 2 minimum limit	4 %	10 %
ETS 2 maximum limit	7 %	20 %
CO_2 tax		
CO_2 tax minimum limit	2,5 %	5 %
CO_2 tax maximum limit	5 %	15 %

Table 1. ETS2 and Carbon tax parameters

In addition to the ETS 2 surcharge, the tax-free price of each fuel type is modelled with Geometric Brownian motion. Diesel prices in Finland are tied to ULSD, which is a global market quote that makes up for a portion of diesel's pump price. HVO being a direct energy source substitute for diesel, it follows the price development of diesel, and therefore, of ULSD as well. Hence, ULSD will be used to set the probability distribution ranges for both fuel types. The ULSD quote has displayed an average growth rate of 6,7% and volatility of 30%. According to these values, the drift and volatility ranges are defined in Table 2. Diesel

is set to fluctuate around the historical values, however, for HVO the corresponding values are brought down to reflect a more conservative view as increasing biofuel mandates increase HVO production and reduce the need for diesel derived pricing.

Similarly to diesel and HVO, the price of LBG follows the price of its fossil counterpart, and a major natural gas quote in Europe is TTF. The average growth rate and volatility over the last ten years have been 7% and 62% respectively. Drift and volatility ranges for LBG are displayed in Table 2. The upper limit of the drift parameter is set to be the average of last ten years, since increase in European LBG production will reduce dependency on global natural gas supply.

	Growth rate (drift)	**Volatility**
ULSD 2016-2025	6,7 %	30 %
Diesel minimum limit	5,5 %	20 %
Diesel maximum limit	8 %	40 %
HVO minimum limit	5 %	20 %
HVO maximum limit	7 %	30 %
TTF 2016-2025	7 %	62 %
LBG minimum limit	4 %	20 %
LBG maximum limit	8 %	40 %

Table 2. Price parameters per fuel type

Unlike HVO and LBG in Finland, where the CO_2 tax is zero, diesel has a CO_2 tax, which is under pressure to be increased as a tool to incentivise sustainable energy sources. Hence, GBM is implemented to this fuel price component as well. Between 2028 and 2040, there will be three different parliaments with a mandate to change the carbon taxes and most likely the tax for fossil fuels will be increased. Therefore, the GBM drift parameter for carbon tax is set at ranges defined in Table 1.

5.2 Price elasticity of demand

The foundation of the price elasticity model used in this thesis is a constant-elasticity demand model, which is common in empirical economic studies, but is also highly restrictive. As the objective here is to estimate the responsiveness of demand to price changes, a reduced form approximation of demand is sufficient rather than a complete structural system (LaFrance 1986). Price elasticity of demand is defined in equation 2:

$$Q_t = Q_{t-1} * (\frac{P_t}{P_{t-1}})^{\varepsilon} \quad (2)$$

where Q represents demand and P represents price in year t, and ε represents elasticity.

The baseline demand assumptions in the PEIKKO report assume that some current diesel-based consumption will be substituted with LBG as an energy source, resulting in diesel and HVO consumption decreasing and LBG increasing over time. The PEIKKO report provides the base demand scenarios for each fuel yearly, which is then adjusted based on price elasticity. As Harju et al. (2025) concluded in their research, price elasticity can vary between -0,7 and -1. Based on their findings, this thesis assumes an average elasticity factor of -0,85.

As the PEIKKO report assumes a 2% yearly inflation rate in its calculation, the price elasticity model in this thesis compliments the PEIKKO calculations with more comprehensive price assumptions.

5.3 Sensitivity analysis

To estimate the robustness of the model and assess relationships between the uncertainty of the output and uncertainty of the input variables in a model, a global sensitivity analysis

provides the means for it. Global sensitivity analysis considers the influence of multiple input parameters' variation in the model output. (Saltelli et al. 2008)

In this thesis, sensitivity analysis is implemented using a browser-based application called SimDec (Simulation Decomposition). SimDec combines Monte Carlo simulation with variance-based sensitivity analysis by decomposing simulation outputs into scenarios based on combinations of the uncertain input variables. This enables estimation of variable importance through sensitivity indices and visual examination of heterogeneous effects. (Kozlova et al. 2024; Kozlova & Yeomans 2024)

Simulation decomposition divides uncertain input variables and their uncertainty distributions into sub-ranges, from which multidimensional scenarios are formed. As each Monte Carlo simulation run produces a result, it also tracks which combination of input conditions were used for that output. Simulation decomposition splits the simulation output into smaller groups, which is composed of specific combination of input conditions. By examining the groups separately, conclusions can be drawn on how different conditions affect the results, particularly in the extremes. In addition, SimDec applies variance-based sensitivity analysis to compute sensitivity indices that measure the relative contribution of individual input variables to output uncertainty. (Kozlova et al. 2024; Kozlova & Yeomans 2024)

6 Results

This chapter presents the outputs from the Geometric Brownian motion and Monte Carlo simulation models specified in the previous methodology chapter. The simulated retail prices of all three fuel types are presented in their retail units of measurement and in euros per megawatt hour (MWh) to improve comparability. Next, demand developments are presented based on price elasticity calculations, which is finally followed by the sensitivity analysis results.

6.1 Prices and demand

6.1.1 Fuel price development

Figures 5-7 present samples of 30 simulated price trajectories for diesel, HVO and LBG that are generated using Geometric Brownian motion and Monte Carlo simulation. These graphs illustrate the stochastic nature of the simulation process and the widening dispersion of possible future price paths over time.

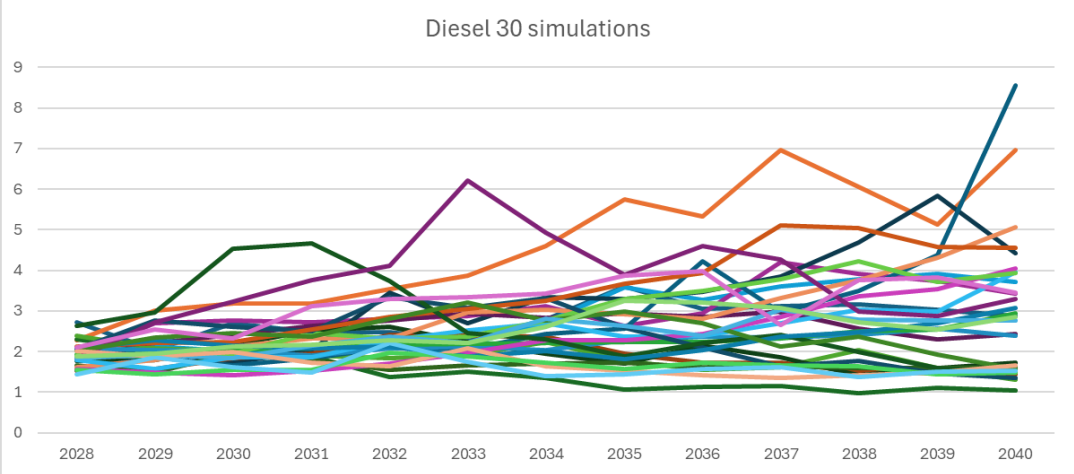

Figure 5. 30 simulated price paths for diesel

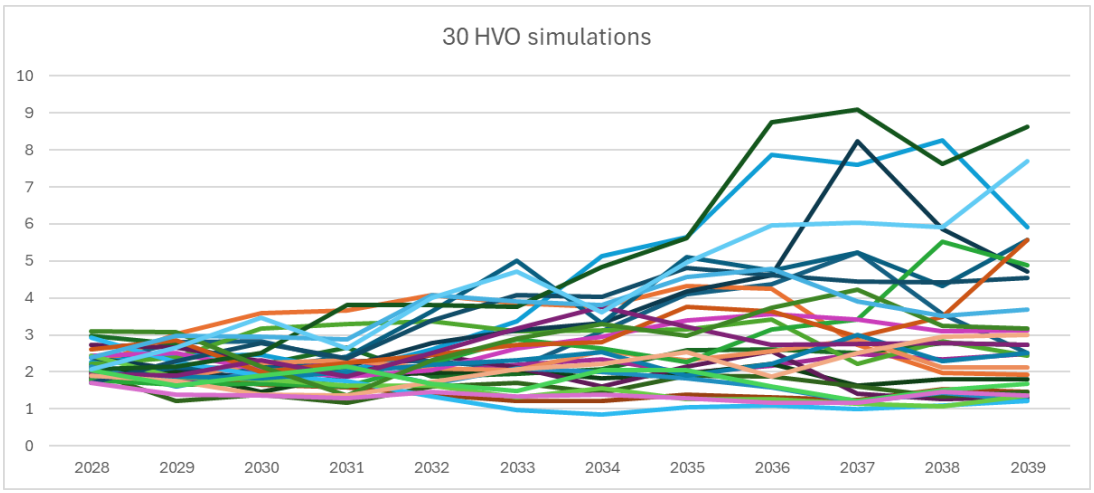

Figure 6. 30 simulated price paths for HVO

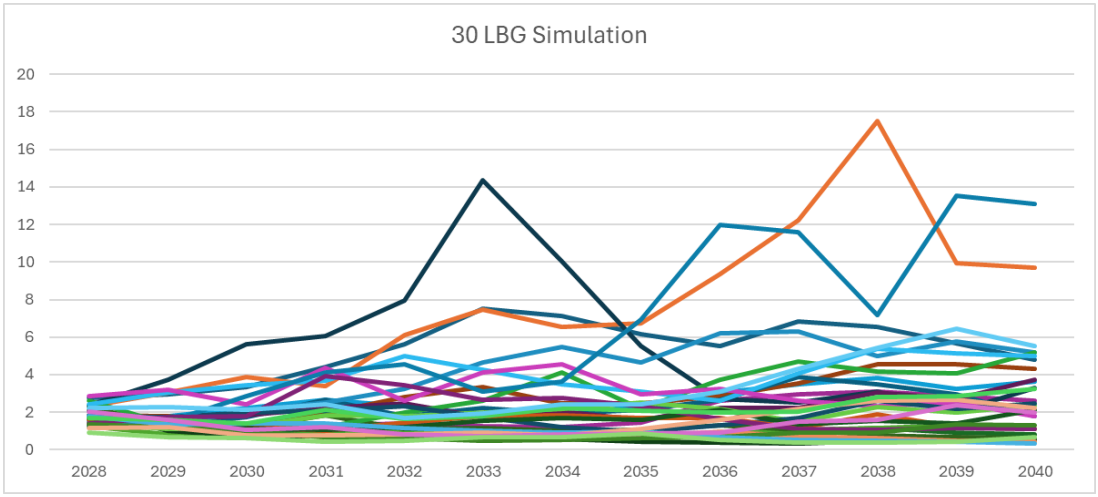

Figure 7. 30 simulated price paths for LBG

For all examined fuels, the spread of simulation paths increases toward the end of the examination period, reflecting the cumulative effect of the volatility parameter in the stochastic process. Compared to diesel, the HVO and particularly the LBG simulations display a wider dispersion of possible outcomes. Although the average price development follows a generally increasing trend, individual simulated paths may deviate substantially from the mean prediction due to the uncertainty incorporated into the model.

The results from the simulations indicate an upward trend in retail prices for all three fuels between 2028 and 2040. Despite demonstrating similar trends, the magnitude of increase differs slightly between the three due to differences in policy mechanisms and market price assumptions. Price developments are shown in Figure 8.

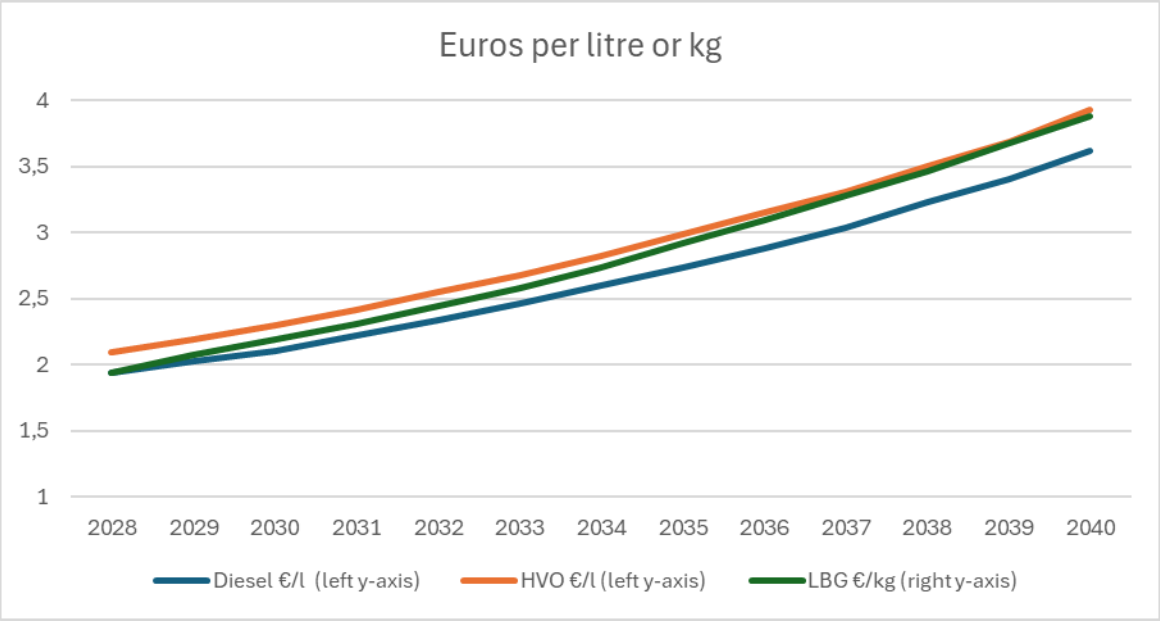

Figure 8. Retail fuel price in euros per retail unit of measurement

Diesel prices are estimated to be at a level of 1,94 €/l in 2028 from where they are to increase to approximately 3,62 €/l in 2040. The increase in the retail price is driven by the stochastic development of the base price element as well as the policy induced cost components of ETS2 and carbon taxation. Other price components have not been subjected to a stochastic process, leaving their contribution to be negligible.

Despite diesel experiencing upward pressure from ETS2 implementation, HVO remains the most expensive fuel throughout the examination period. The average price rises approximately by 1,84 €/l from 2,09 €/l in 2028 to 3,93 €/l in 2040. Although HVO benefits from non-existent carbon taxation compared to fossil diesel, its high production related costs keep HVO more expensive than diesel during the whole examination period.

LBG displays the lowest price level of the three fuels, however, due to differences in retail units of measurement, it is not directly comparable as it is priced in euros per kilogram. The

simulated price of LBG increases from 1,94 €/kg in 2028 to 3,88 €/kg in 2040. Similarly to HVO, LBG benefits from a zero percent carbon tax.

To improve comparability between fuels with different energy contents and retail units, prices were converted into euros per MWh. This conversion provides better insight to the relative prices of the three fuels. As is clearly evident from Figure 9, LBG remains the most cost-efficient fuel type in terms of energy content throughout the whole examination period. In 2028, one MWh of LBG would cost around 140 euros compared to 194 €/MWh for diesel and 221 €/MWh for HVO. In 2040, those numbers are 279 €/MWh for LBG compared to 362 €/MWh for diesel and 416 €/MWh for HVO.

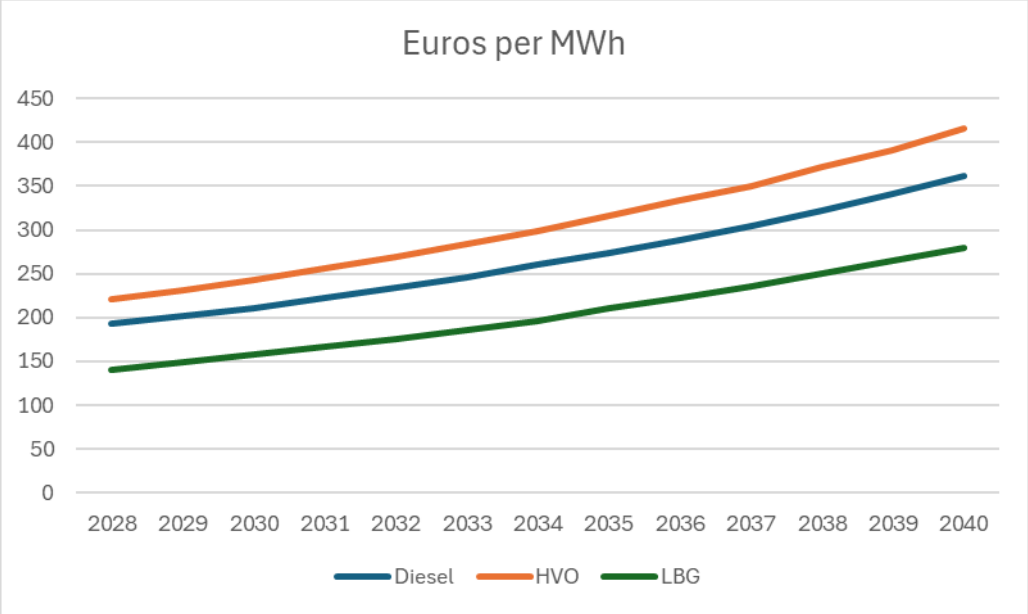

Figure 9. Retail fuel price in euros per MWh

Table 3 compares the prices calculated for the first and last year of the examination period. In the beginning LBG is approximately 54 €/MWh cheaper than diesel and over 80 €/MWh cheaper than HVO. The differences to diesel and HVO in 2040 are 83 €/MWh and 137 €/MWh respectively. While has the highest absolute price increase, LBG has the highest percentage increase, effectively doubling during the examination period.

	€/MWh in 2028	€/MWh in 2040	€-difference	%-difference
Diesel	193,96	366,39	172,43	88,9 %
HVO	221,94	409,47	187,54	84,5 %
LBG	138,82	270,66	131,84	95,0 %

Table 3. Relative price increases between fuel types

6.1.2 Demand development

The results from the price elasticity model indicate decreasing demand for diesel and HVO over the examination period, while demand for LBG increases steadily. Diesel demand decreases from approximately 194 thousand tons in 2028 to approximately 110 thousand tons by 2040 and HVO demand declines from 124 thousand tons to less than 63 thousand tons. LBG on the other hand, more than doubles from 8,9 thousand tons to approximately 18 thousand tons. These developments are specified in Table 4.

	Demand 2028	Demand 2040	Difference	%-difference
Diesel	194 078,77	109 764,43	-84 314,34	-43,4 %
HVO	124 171,04	63 257,10	-60 913,94	-49,1 %
LBG	8 932,31	18 483,78	9 551,46	106,9 %

Table 4. Relative demand developments between fuel types

Figure 10 demonstrates the demand trend of each fuel type. The most noticeable developments occur in diesel and HVO demand during the first four years, where diesel demand decreases rapidly until 2031 and HVO remains quite stable, even showing a slight increase in 2030. Thereafter, both fuels experience comparable decreasing trends until 2040. LBG demand decreases until 2029 but displays steep growth all the way to 2040.

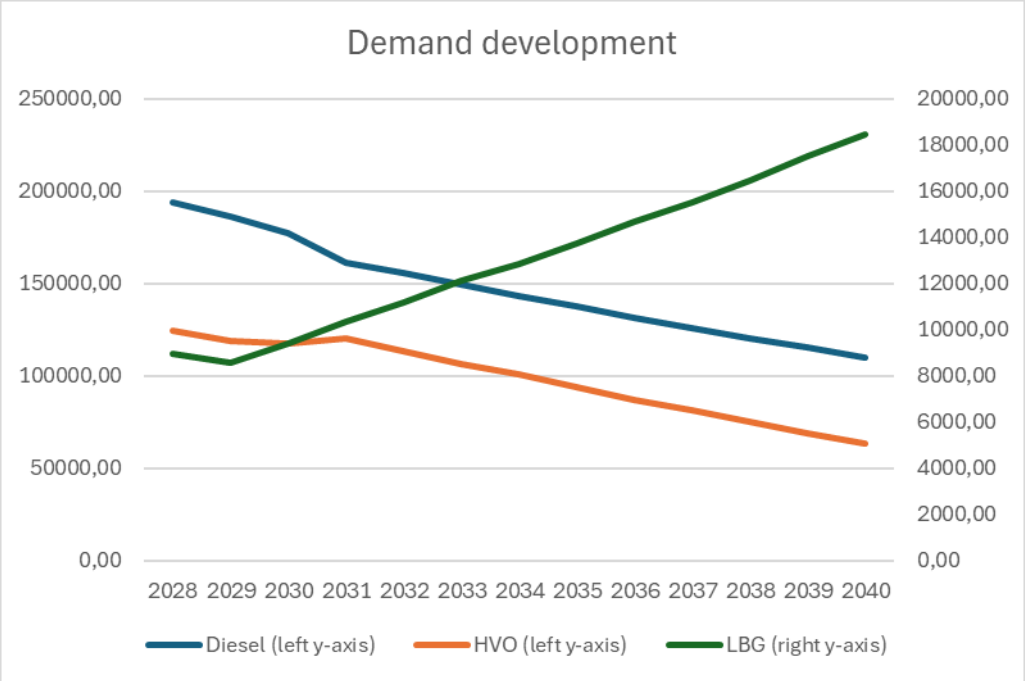

Figure 10. Demand development per fuel type

6.2 Sensitivity analysis

Sensitivity analysis was conducted using SimDec to estimate the influence of each stochastic input variable on the variance of the output. The sensitivity analysis focused on the final simulated retail price in 2040 for each fuel, diesel, HVO and LBG. Variance-based sensitivity indices were used to measure the contribution of each input parameter to the variance of the output variables.

For diesel, the sensitivity analysis indicates that the largest contribution to output variance is associated with the tax-free base price in 2040. The sensitivity index of the base price is 0,55, while the sum of all indices is 0,60 as is shown in Table 5. The remaining variables, including base price drift, ETS2 drift, carbon tax drift, base price volatility and carbon tax volatility, each receive substantially smaller indices of approximately 0,01 or less. This indicates that the final diesel retail price variation is primarily related to the base price component. The individual indices are approximate values, which do not add up to a precise sum and therefore can deviate from the calculated sum of indices.

Inputs	**Indices**
Base 2040	0,55
Base drift	0,01
ETS 2040	0,01
CO2 tax drift	0,01
ETS drift	0,01
Base volatility	0,01
CO2 tax volatility	0,01
ETS volatility	0,00
CO2 tax 2040	0,00
Sum	**0,60**

Table 5. Diesel sensitivity indices

Based on the sensitivity indices, the first two input variables are selected for further sensitivity analysis. Figure 11 demonstrates how base drift is decomposed into scenarios and sub-scenarios, when Base 2040 is included. In every scenario, where the Base 2040 is high, the maximum value of the distribution is significantly higher than in the low and medium scenarios. This is also evident from the standard deviations. Low and medium scenarios are always between 0,4 and 0,45, while in the high scenarios this increases to 2,75.

Scenarios

Base drift	Base 2040	N°	colour	std	min	mean	max	probability
low	low	9		0.44	0.74	1.87	3.52	0.12
	medium	8		0.41	2.27	3.07	4.57	0.11
	high	7		2.88	3.55	5.75	40.97	0.10
medium	low	6		0.45	0.71	1.89	3.76	0.11
	medium	5		0.43	2.25	3.07	5.02	0.11
	high	4		2.75	3.59	5.82	49.85	0.11
high	low	3		0.43	0.75	1.88	3.39	0.10
	medium	2		0.44	2.24	3.11	5.50	0.11
	high	1		3.60	3.52	6.05	90.17	0.13

Figure 11. Diesel scenario analysis for Base 2040 and Base drift inputs

The sum of the sensitivity indices for the diesel model remains under one, which is initially unexpected. According to Kozlova et al. (2024) and Kozlova & Yeomans (2024), this can occur when variance-based sensitivity analysis is applied to outputs that follow lognormal distributions, causing underrepresentation of tail effects by the variance decomposition. In this thesis, the final retail price is fully determined by the stochastic price components in the final year, and as the components are generated through Geometric Brownian motion processes, the output distributions display lognormal behaviour. Figure 12 demonstrates how part of the uncertainty remains in the tails of the distributions and is not captured by the sensitivity indices. These wide distributions occur in scenarios 1, 4 and 7, referring to the scenarios, where the input variable Base 2040 is high.

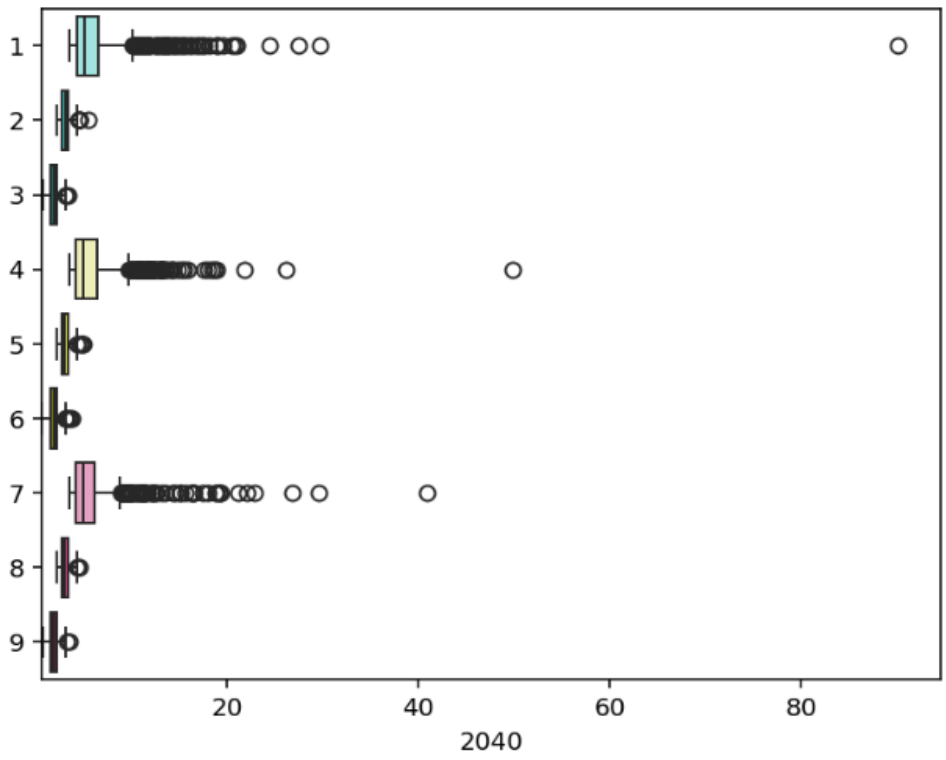

Figure 12. Diesel boxplot of full distributions for Base 2040 and Base drift inputs

To gain a closer visual look into the scenario distributions, the x-axis is truncated into [0, 10], which can be observed in Figure 13. Particularly in the high scenarios, the boxplots and their whiskers demonstrate the uncertainty of the wide distributions already specified in Figure 11. Figure 13 shows much more moderate boxplots for low and medium scenarios. Each box is situated approximately in the middle of the distribution, and the median value is roughly in the middle of the boxes, implying a rather symmetric distribution.

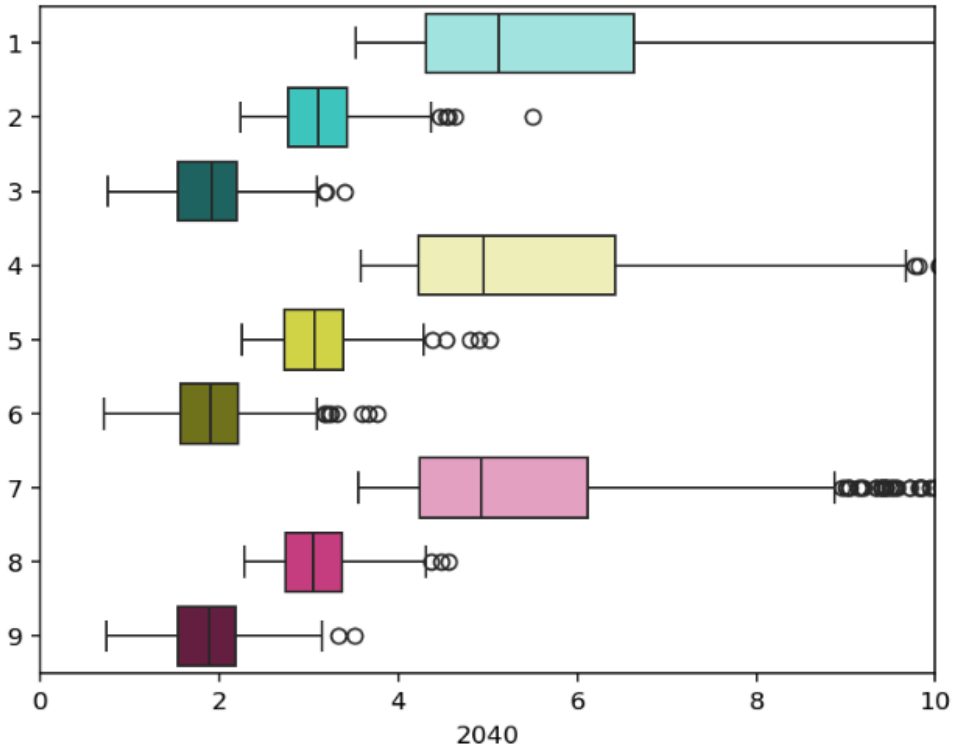

Figure 13. Same boxplot as Figure 12 with truncated X-axis

For HVO, the sensitivity analysis shows that the final base price in 2040 accounts for nearly all of the output variance. Table 6 shows that the sensitivity index for the base price is 0,98, while base drift and base volatility both receive indices of approximately 0,01. The sum of the indices is 1,00. The scenario results demonstrated in Figure 14 show a strongly skewed distribution in the high price group, where the maximum value is considerably larger than the mean value.

Inputs HVO	Indices
Base 2040	0,98
Base drift	0,01
Base volatility	0,01
Sum	**1,00**

Table 6. HVO sensitivity indices

Scenarios

Base 2040	Base drift	Base vol.	N°	colour	std	min	mean	max	probability
low	low	low	8		0.54	0.51	1.73	2.72	0.12
		high	7		0.58	0.46	1.54	2.72	0.14
	high	low	6		0.55	0.55	1.79	2.72	0.11
		high	5		0.59	0.50	1.61	2.72	0.13
high	low	low	4		3.55	2.72	5.58	50.40	0.13
		high	3		5.66	2.72	6.46	90.77	0.11
	high	low	2		4.18	2.72	5.91	54.30	0.14
		high	1		5.86	2.72	6.74	72.79	0.12

Figure 14. HVO scenario analysis for Base 2040, Base drift and Base volatility inputs

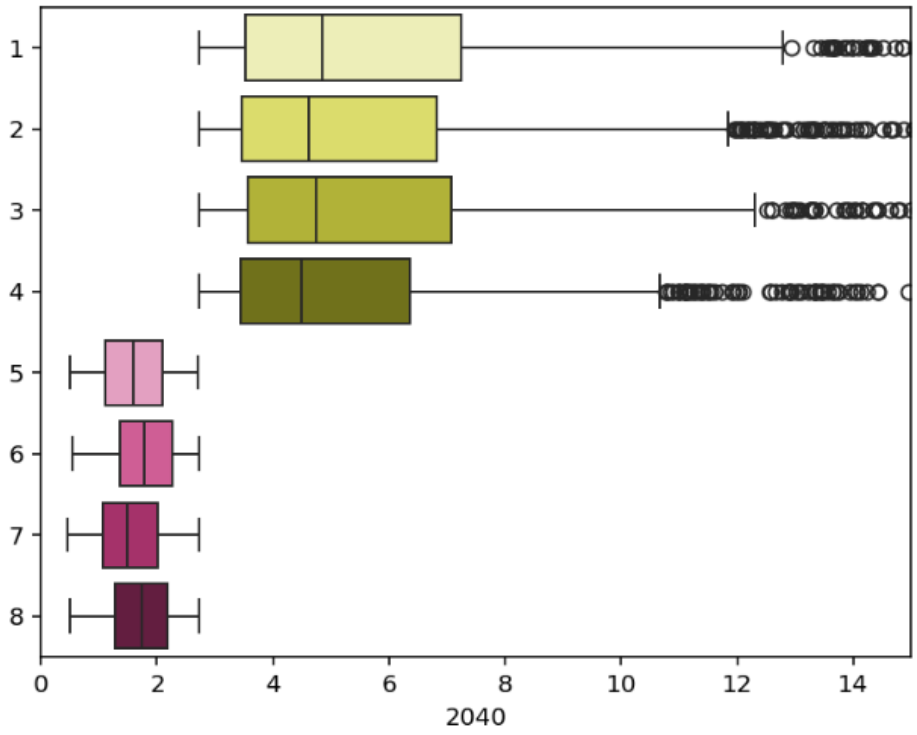

Figure 15. HVO boxplot with truncated X-axis for Base 2040, Base drift and Base volatility inputs

Table 7 confirms that the results for LBG are similar to HVO. The sensitivity index for the base price in 2040 is 0,99, while base volatility and base drift each receive indices of roughly 0,01, resulting in a 1,01 as the sum of indices. As with HVO, the scenario results for LBG displayed in Figure 16 and Figure 17 show wide tails in the high base price scenarios compared to the mean value. Since HVO and LBG are not subject to ETS2 or carbon taxation in the same way as diesel, only the tax-free base price component has a stochastic process for these fuels.

Inputs LBG	Indices
Base 2040	0,99
Base drift	0,01
Base volatility	0,01
Sum	**1,01**

Table 7. LBG sensitivity indices

Scenarios

Base 2040	Base drift	Base vol.	N°	colour	std	min	mean	max	probability
low	low	low	8		0.49	0.21	1.29	2.22	0.12
		high	7		0.56	0.19	1.04	2.21	0.15
	high	low	6		0.50	0.33	1.37	2.21	0.09
		high	5		0.55	0.19	1.06	2.21	0.14
high	low	low	4		4.49	2.22	5.45	56.42	0.13
		high	3		8.21	2.22	7.31	68.25	0.10
	high	low	2		5.18	2.22	5.93	68.65	0.15
		high	1		8.66	2.23	7.60	78.51	0.12

Figure 16. LBG scenario analysis for Base 2040, Base drift and Base volatility inputs

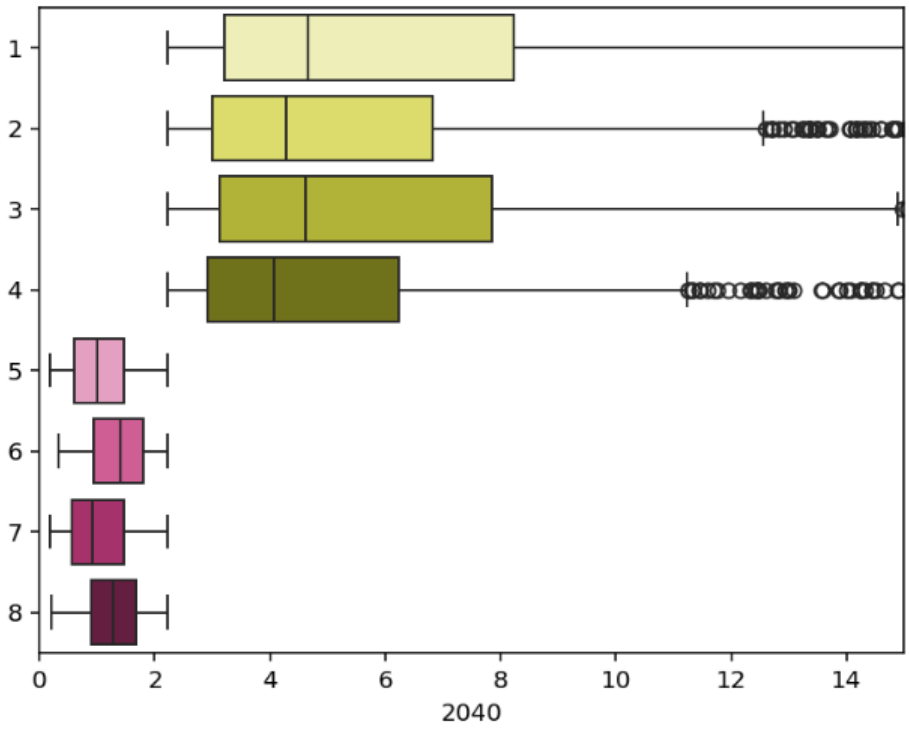

Figure 17. LBG boxplot with truncated X-axis for Base 2040, Base drift and Base volatility inputs

7 Conclusions and discussion

The objective of this thesis was to analyse how the relative prices and demand outlook of diesel, HVO and LBG develop under uncertainty in fuel pricing components. The thesis combined Geometric Brownian motion and Monte Carlo simulation with price elasticity calculations to examine the future development of three road transport fuels in Finland. The study focused on both market driven price components and policy-driven cost components, particularly ETS2 and carbon taxation.

The first research question aims to answer how the price relativity of diesel, HVO and LBG is expected to develop under uncertainty in fuel price components. The results indicate that all three fuels experience increasing retail prices during the examination period from 2028 to 2040, where relative price order between the fuels remains stable in the model throughout the examination period, LBG being the cheapest alternative and HVO being the most expensive. However, the relative differences between fuels are affected by both market price assumptions and policy components. Diesel is the only fuel in the model directly affected by both ETS2 and carbon taxation, which increases the role of policy-driven costs in its future price development.

The modelling outcome is aligned with previous literature on stochastic modelling in energy and carbon markets. Earlier research has shown that GBM and Monte Carlo simulation can be useful for producing baseline forecasts under uncertainty, but that the method is sensitive to parameter assumptions and limited in its ability to capture sudden market shocks (Pindyck 1999; Mosiño & Moreno-Okuno 2018; Lee & Ham 2023). The simulated price paths in this thesis follow this pattern, as the average price paths are relatively smooth and increasing, while individual simulation paths display widening dispersion over time.

The second research question examined the impact of fuel price on demand. In the model, fuel price changes affect demand through the elasticity factor, where the overall demand outlook is connected to the baseline development assumptions provided by the data. As the PEIKKO report assumes a 2% yearly inflation rate in its calculations, the price elasticity model in this thesis compliments the PEIKKO calculations with more comprehensive price assumptions. With an elasticity factor of -0,85, the model produces lower consumption levels for the examination period than the PEIKKO baseline for all fuels.

The sensitivity analysis supports the importance of parameter assumptions in the model. As the model for diesel includes multiple stochastic processes compared to only one in the case of HVO and LBG, a direct comparison between sensitivity results is difficult. If the renewable fuels would have been subject to a stochastic process for carbon tax as well, the parameters would have had to be quite conservative to be realistic. Based on the rather small sensitivity index measured for diesel, it is very likely that similar sensitivities would have been measured for HVO and LBG as well.

The SimDec analysis for diesel demonstrated a methodological limitation related to variance-based sensitivity indices. As was mentioned earlier, the low the sum of sensitivity indices suggests that the distribution of the output follows a lognormal behaviour, leaving tail effects out from the variance decomposition (Kozlova et al. 2024; Kozlova & Yeomans 2024). This is relevant in this thesis, because the retail prices of the final year are generated by stochastic processes, leaving some uncertainty in the tails of the simulated distributions. However, this does not change the bigger picture, which clearly shows the significance of the base price in the variation of the output.

The results emphasize the importance of considering both market price uncertainty and policy-driven costs when analysing future fuel competitiveness. The model indicates that relative fuel prices may develop differently depending on the fuel type, even though all fuels are experiencing increasing prices. For an energy company, this means that future competitiveness of fuels cannot be assessed only by comparing current retail prices, but should also include assumptions regarding future commodity prices, carbon allowance pricing, taxation and demand response.

The significance of portfolio analysis is increasingly important in a policy environment, where fossil and renewable fuels are affected differently by regulation. For now, diesel remains exposed to carbon taxation and ETS2, while HVO and LBG benefit from more favourable taxation. However, regulation can be changed in either direction whenever there is enough support for it. Additionally, renewables alternatives are not automatically less expensive, as HVO remains the most expensive option due to its higher base price. This highlights the importance of considering policy exposures as wells as underlying production and sourcing cost.

This thesis provides a transparent way to examine these relationships, since the calculation logic is adjustable to be updated with new market price and ETS2 data or if company-specific assumptions is available. This is particularly relevant, as the ETS2 market is still illiquid at the time of writing this thesis and is very speculatory on the future price levels.

7.1 Final comments and future research

Overall, this thesis contributes to existing literature by combining stochastic price modelling and demand elasticity into one analytical framework. Previous literature has studied these elements separately, but there is less research on how they interact across competing transport fuels under uncertainty. By applying the model to diesel, HVO and LBG in Finnish road transport, the thesis provides a comparative perspective on future fuel price and demand development in a changing regulatory environment.

The main finding suggests that all examined fuels become more expensive during the examination period, but their relative price differences widen over time. LBG remains the cheapest and HVO the most expensive fuel, while diesel is increasingly affected by policy-driven costs. Demand for diesel and HVO decreases in the model, while LBG demand increases, concluding that future fuel market development is shaped by the combined effect of market prices, regulation and substitution possibilities rather than by one factor alone.

Future research should focus more on retail price modelling in Finland that captures sudden market shocks and irregular price patterns to gain a more accurate projection into the future by utilizing more advanced stochastic processes, such as jump diffusion models. Demand and therefore price developments are heavily influenced by fuel mandate levels. In this thesis they were kept at the levels that are defined in the current legislation but can be changed by the government at any time, which will affect price and substitution dynamics. Including a scenario analysis on mandate levels would be useful for energy companies in their strategic decision making.

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