REPORT

Borgarlína BRT System Fuel Selection Study

Final report

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Executive summary

The study

The Borgarlína is the new Bus Rapid Transport (BRT) system in Reykjavík area, connecting most capital area destinations. Borgarlína wants to set a standard on using clean domestic fuel. Therefore, a study on the best, future-proof fuel available was initiated by Landsvirkjun, Strætó bs., the association of Municipalities in the Capital Area) and the Public Roads Administration of Iceland. For this purpose, three major options have been regarded:

- Battery-powered Electric Vehicles (BEV, 2 scenario's)
- Fuel Cell powered Electric Vehicles (FCEV, Hydrogen)
- Internal Combustion Engines (ICE) using CNG

This study compared qualitative and quantitative aspects of all options to the current use of diesel-fuel and considered for the purpose of this study three phases of the implementation of the Borgarlína network.

- Phase 1: Borgarlína lines A, B, C and 25% of the fleet of Strætó bs. (2024)
- Phase 2: Borgarlína lines A, B, C, D, F and entire fleet of Strætó bs. (2029)
- Phase 3: Borgarlína lines A, B, C, D, E, F and entire fleet of Strætó bs. (2034)

A complete online overview of the current bus lines, end stations and hubs is available here[1]. This visualisation based on the map of Reykjavík shows all the relevant geographical information for this study.

Approach

To ensure a fair comparison of options, a total cost of ownership (TCO) overview, considering all costs over the lifespan of the project, has been made. The TCO approach includes both the initial investment costs of the assets, as well as the costs to maintain and operate the assets over a predefined period of time. This time period is often set to the asset's lifespan.

Calculation was based on the following input:

- costs of the vehicles
- costs of necessary energy infrastructure (including transport and fuelling points)
- costs of the fuel
- cost of operating the network (including maintenance)

All scenarios are compared to a 0-scenario, based on diesel vehicles. Currently the fleet contains 2 new Methane buses and 15 plug-in charged Diesel heated electrical buses. To estimate the total cost of ownership, it is important to determine the size of the fleet of the network for each phase, and the amount of yearly travelled kilometers as indicated in Table 1.

Phase	Line	Vehicles	Yearly km (estimate)
1	A	7	889,000
	B	7	934,000
	C	6	973,000
1/2	Strætó network	121	9,600,000
2	D	6	1,073,000
	F	6	900,000
3	E	7	1,183,000

Table 1 - Vehicles and kilometers

[1] *https://vso.maps.arcgis.com/apps/webappviewer/index.html?id=1c0d7cc776104d7cb710033e7099951c*

To enable a fair comparison between scenarios and account for the time value of money, a present value calculation was added to the analysis and applied to the real cash flows from the TCO model. This summarises the total cost of ownership in one monetary amount in the present and enables fair comparison of different scenarios. For the present value calculation, a real discount rate of 3% was applied to the real cash flows.

Besides emissions, noise, weight and vibrations other environmental aspects were taken into account. Each fuel system has its own impact on the environment with its own advantages and challenges. Table 2 shows a qualitative description of each fuel system.

	BEV (electric)	FCEV (Hydrogen)	Natural gas (CNG/LNG/Bio)
Advantages	• Zero-emission and air quality[2] • No safety risks due to explosive atmospheres • Noise reductions if compared to ICE on diesel fuel	• Zero-emission and air quality • Short refuelling time • Less weight if compared to ICE and BEV • Lower material footprint • Suitable for long distances • Less costs for personnel • Noise reductions if compared to ICE on diesel fuel	• Close-to-zero PM emissions and less NOx if compared to ICE on diesel fuel • Flexible in use • Suitable for long distances • Small noise reductions if compared to ICE on diesel fuel
Main challenges	• Limited vehicle range, especially when cold • Frequent charging needed, which takes time and has an influence on operations • Heavy charging infrastructure needed • Weight of the battery • Use of scarce resources for the battery (social and geopolitical risks) • Limited lifetime of batteries • Increased fire safety risks in charging stations and in the vehicle	• Hydrogen is only 'green' if produced by electrolysis, powered by green electricity. (Worldwide most Hydrogen is produced out of Methane) • Low utilisation of tank station (adds up infrastructural costs) • Production costs of Hydrogen are high (in general for both CAPEX and OPEX and previous bullets will add costs) • Energetic losses in production, transmission and storage are higher compared to BEV • Increased safety risks due to explosive atmospheres • Limited lifetime of fuel cells	• CNG / LNG are still emitting CO2, not "zero-emission" • Caloric value of biogas may differ in time • Contaminations in the biogas may lead to unwanted emissions • Gas treatment installations reduce the total energy efficiency of the transport system • Possibility of Methane slip in production, transportation and consumption of Methane
Availability vehicle	• Batteries have become more efficient and have larger capacity (now up to 525 kWh) • Availability has been improved in recent years • Maintainability has been approved	• Installed base is still limited (many pilots ongoing but the number of full-scale projects in operation is still limited) • There are currently no manufacturers that produce 24 meter fuel cell buses, but new models are expected from major manufacturers	• 'Off the shelf' vehicles with proven technology • Contaminations in the biogas may lead to extra maintenance demands
Availability infrastructure	• The capacity of the electricity grid may be limited	• Fenced area is required for fuel storage and treatment • Safety area and restricted area around the fuel storage are required	• Existing infrastructure may be used, this depending on gas composition and possible contaminations in the gas

[2] *With exception of buses with diesel heaters*

	• Overnight and OC (opportunity charging) required		
Future development until 2030	• Innovations in battery technologies will take place • Battery: <= 1.000 euro per kWh (max ca 500 kWh) • More competitive costs of opportunity chargers will appear • More uniformity in charging infrastructure • Better end-of-lifetime perspectives for batteries	• Innovations in fuel cell technology will take place • Costs of Fuel Cells will get more competitive • With other applications for Hydrogen the availability will increase	

Table 2 - Qualitative description of each fuel system

Total Cost of Ownership

The zero alternative (diesel) scores the highest in terms of costs, followed by CNG, electricity (diesel heated) and Hydrogen. Electricity (in both full electricity scenarios) is the most expensive alternative, mostly because of the investments needed in electrical infrastructure. Since lease prices are used for all scenario's, the replacement times and costs of vehicles and batteries are distributed evenly over the years.

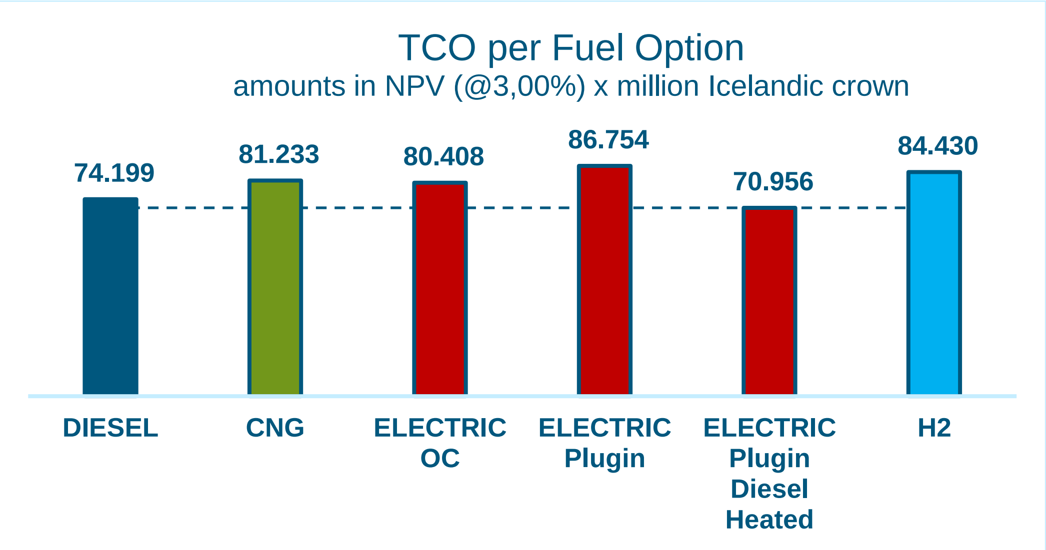

Figure 1 - TCO per scenario (x million ISK, excl. VAT in PV @3%)

A sensitivity analysis is made to investigate the impact of the CNG and Hydrogen prices on the Total Cost of Ownership. The sensitivity analysis shows that the prices of Hydrogen and CNG matter. If the Hydrogen price is lowered, the TCO is competitive with CNG.

Impact on the environment

Besides, the costs of the investment, the impact on the environment was equally important. Therefore, the emissions of the different fuels were compared in a quick scan. The actual emissions and impact of other environmental issues (e.g. vibrations) require accurate input (air-inlet temperatures, surface and building reflection characteristics) and can only be determined by more detailed calculations and measurements.

The impact analysis focussed on CO_2 (Climate), PM_{10} and NO_x (local air quality). In addition, noise, weight and vibrations were investigated. The emissions are depending on mainly three factors in the following order:

1. The type of fuel
2. The type of bus
3. The type of lines

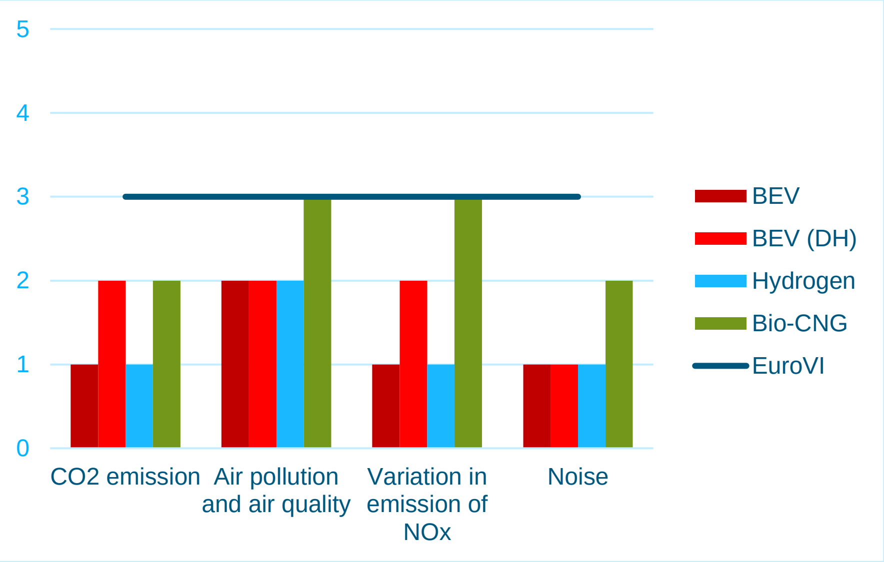

Figure 2 - Environmental impact of fuel systems compared to Diesel (Euro VI)

The outcome of the impact analysis is shown in Figure 2. A comparison on weight and vibration is only made qualitatively and therefore not shown in the figure.

Conclusion

The findings of the study are summarised in an assessment framework, to provide an overview over the various scenarios. Diesel is considered the bases scenario and therefore not part of the assessment framework. All sustainable fuels are scored against the base scenario (diesel), and if needed provided with summarised context.

Fuel	Methane	Electricity (OC)	Electricity (PI)	Electricity (DH)	Hydrogen
TCO	**0/-** 81M ISK Sensitivity Lower CNG prize (25%) **0/-** 78M ISK	**0/-** 80M ISK	**-** 87M ISK	**+** 71M ISK	**-** 84M ISK Sensitivity Lower H2 prize (25%) **0/-** 81M ISK
Lifetime GHG emissions (Kg CO_2/km WTW)	**+** 0.15-0.2	**++** 0.0019-0.0037	**++** 0.0019-0.0037	**0/+** 0.267-0.271	**++** 0.013
Local emissions	**0** 0.015	**++** 0	**++** 0	**+** 0.001	**++** 0

PM_{10} (exhaust g/km) PM_{10} (wear g/km) PM_{10} (total g/km) NO_x (avg g/kg	0.092 0.107 0.6-0.69	0.068 0.068 0	0.068 0.068 0	0.068 0.069 0.06-0.08	0.068 0.068 0
Noise levels	**+**	**++**	**++**	**++**	**++**
Vibrations		To be determined			
Weight of vehicles		The differences between models of the same fuel type is greater than the difference between fuel types			
Spatial impact	**0** Most infrastructure is already available	**--** Infrastructure for opportunity charging at hubs has a big spatial impact on the area around several hubs.	**0/-** Plug-in infrastructure at the depot needed	**0/-** Plug-in infrastructure at the depot needed	**0/-** Filling station close or at the depot needed.

The outcome of TCO model shows the electrical plug-in scenario to be the most expensive. Electricity (opportunity charging), methane and hydrogen score better in terms of costs, despite of the higher vehicle costs. The least expensive scenario is the electrical plug-in scenario with diesel heaters. This scenario is competitive with diesel.

Since CNG is a proven technology with a present infrastructural network, and Hydrogen is a technology in development, the costs of the Hydrogen vehicles are expected to be lowered over time. The costs of electrical vehicles are also expected to decrease some more, but not in the same extend as Hydrogen vehicles. Part of the shift towards affordable vehicles has already been made in the field of electrical vehicles. The sensitivity analysis shows that a lower Hydrogen price makes the total costs of ownership comparable with the costs of CNG.

The goal of the study was to determine the best sustainable fuel available. The scope of the study exceeds just the determination of costs, but also considers the wider impact of the use of each vehicle. The emissions are an important factor and will determine the future image of the Borgarlína network. CNG is considered a sustainable fuel, but scores lower than the alternatives in terms of lifetime emissions and local emissions. Electricity and Hydrogen are a more sustainable alternative regarding emissions, considering the fact that green electricity and green Hydrogen will be used. Using a diesel heater on electric buses causes local emissions (in between CNG and full electrical buses), even when using 100% biodiesel (B100).

Based on the combination of the total cost of ownership and impact on the environment, **both Hydrogen and electricity (plug-in) are suitable and future-proof sustainable fuels for the Borgarlína network**. Compared to CNG and electricity with the use of diesel heaters, the wider impact on the environment and the future of the technology are decisive factors. The spatial impact and the lack of flexibility are the main factors not to choose the electricity scenario with opportunity charging. Between Hydrogen and electricity (plug-in), hydrogen has the advantage of the lower costs and the strong development of technology, where electricity can make use of a growth model with the use of diesel heaters to overcome range issues.

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1 Introduction

1.1 Background

Landsvirkjun, Strætó bs., the association of Municipalities in the Capital Area and the Public Roads Administration of Iceland have signed a cooperation agreement to initiate a study on the best, future-proof fuel available for the Borgarlína project. The Borgarlína is the new BRT system in Reykjavík area, connecting most capital area destinations. This BRT system is still under development.

Besides high-quality service, speed and reliability, Borgarlína also wants to set a standard on using clean domestic fuel. Electricity, Hydrogen and Methane from landfill gas are possible carriers of energy. This Fuel Selection Study will provide a comparison between those energy carriers (fuels). Relevant aspects of these energy carriers will be studied in terms of Total Cost of Ownership (TCO), life cycle analysis, spatial impact, emissions, noise levels, vehicle weight and other relevant factors. The study is crucial in supporting the fuel selection decision for the Borgarlína project.

The main objective of this project is to select the best, future-proof fuel for public transport in the capital area, with regard to total cost of ownership (TCO), environmental factors, passenger experience, and practicalities such as availability of buses and infrastructure. The study will include substantiated and quantified comparison of battery electricity, Hydrogen and Methane (landfill) gas as fuel sources for three different phases of future development. Based on the results of this study, the project owners make a final decision on the choice of fuel.

1.2 Phases

To ensure this objective is met, the Fuel Selection Study must cover all aspects of the different fuels for both, the entire Borgarlína network and the entire fleet of Strætó bs. This does not only include capital investments and operational costs, but also includes emissions, noise and safety aspects. For the purpose of this study, the Borgarlína network is considered to be implemented in three phases:

- Phase 1: Borgarlína A, B, C and 25% of the fleet of Strætó bs. (2024)
- Phase 2: Borgarlína A, B, C, D, F and entire fleet of Strætó bs. (2029)
- Phase 3: Borgarlína A, B, C, D, E, F and entire fleet of Strætó bs. (2034)

The timeline for implementation of the new Borgarlína lines can change over time. The fleet of Strætó will be transformed gradually into a fleet with buses on sustainable fuels. Currently the fleet contains 2 new Methane buses and 15 plug-in charged Diesel heated electrical buses. Experiments with Hydrogen buses were also planned, but didn’t succeed yet, because the tender led to one offer vehicle prices above the acceptable limit for Strætó. A new tender might lead to new insights.

1.3 Method

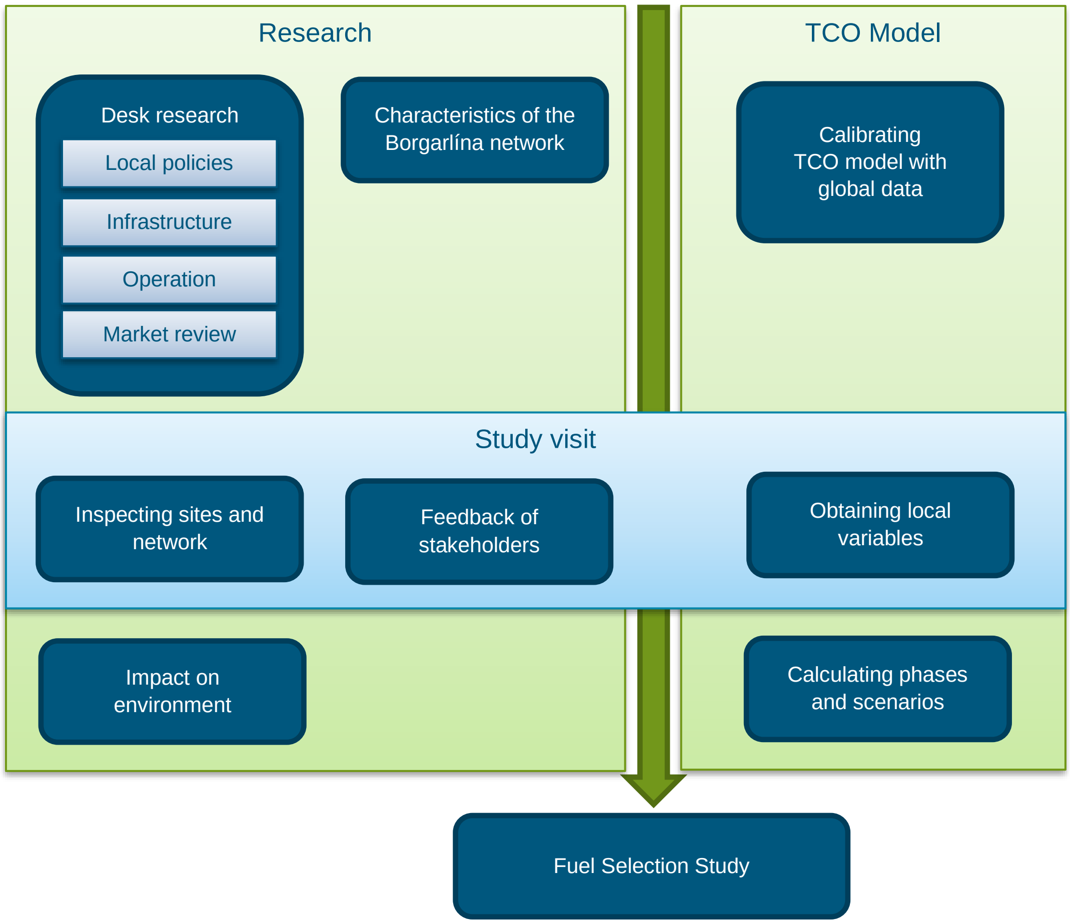


Figure 3 - Method towards a Fuel Selection Study

1.3.1 Phase 1: Investigation

To compare the different fuel options, the surrounding environment needs to be described. Important aspects are:

- Current network
- Future size of the fleet. The intended frequency and trip time of every line of the Borgalína is already known[3]. Based on those measures, a network study is performed to determine the number of buses needed, including a regular reserve and buffer for maintenance.
- Characteristics of the important hubs within the network in order to investigate the spatial adjustments regarding the selected fuel system.
- Logical locations of refuelling stations, given the operations.
- Current available infrastructure like charging possibilities, refuelling stations, pipelines, Methane production and electric infrastructure.

Part of the investigation phase is the desk research, supporting the analysis phase. The desk research is directed at local policies and characteristics of the four considered fuel systems (Electricity, Hydrogen, Methane and diesel):

[3] https://platform.remix.com/map/c4cedc1?latlng=64.10662,-21.95032,10.709&lang=is

- Local sustainability policies, like fuel tax policies, spatial planning policies and environmental policies.
- Infrastructure: What infrastructure is required for each fuel system (refuelling facilities, road structure depending on vehicle weight etc), and what is the spatial and infrastructural impact of all fuels?
- Operation: What is the impact of each fuel system on the operation (driving range, refuelling time, personnel costs, fuel costs)?
- Market review of technology

Each type of fuel has its own characteristics that need to be considered, and its own impact on the environment. This impact is broader than costs, and consists of factors as emissions, noise, vibrations, vehicle weight and safety. Those factors will be considered in chapter 5 and part of the final assessment framework.

1.3.2 Study trip

A study trip to Iceland gave us feedback on the research with local stakeholders. These stakeholders all have their own view on the solution, based on their own perspective, experience and stake. The input and feedback received is weighed and put into perspective. For this study, the following stakeholders were consulted:

- The Borgarlína board
- The Borgarlína team
- Sorpa, a waste management company and producer of Methane out of landfill gas from waste.
- Landsvirkjun, the National Power Company of Iceland
- Strætó bs., the operator of the bus network in Reykjavík.

The interviews were also used to obtain local variables for the TCO model of phase 2 from the various stakeholders. Those variables make sure the output of the model is consistent with the local situation.

1.4 Phase 2: TCO model

The Total Cost of Ownership is calculated by using a Dutch TCO-model, originated from the non-profit foundation CROW. The model is filled with international standard cost figures and calibrated with local input from Iceland. The designer of the model assists in calibrating the model, making sure it is used as intended. The model is iterative, and the outcome can be used to calculate more scenarios in the future.

The model considers the investment cost of the fleet of zero-emission vehicles, the cost of operating it and the costs of the needed infrastructure such as charging facilities. All scenarios are compared to a 0-scenario, based on diesel vehicles.

1.5 Phase 3: Outcome and advice

Based on the outcome of the TCO model, and the investigation on the wider impact on the environment, an assessment framework is used to summarise the findings. Both quantitative and qualitative values are put into perspective and provide advice towards the best sustainable fuel to use for the Borgarlína network.

2 The public transport network

2.1 Current Strætó network

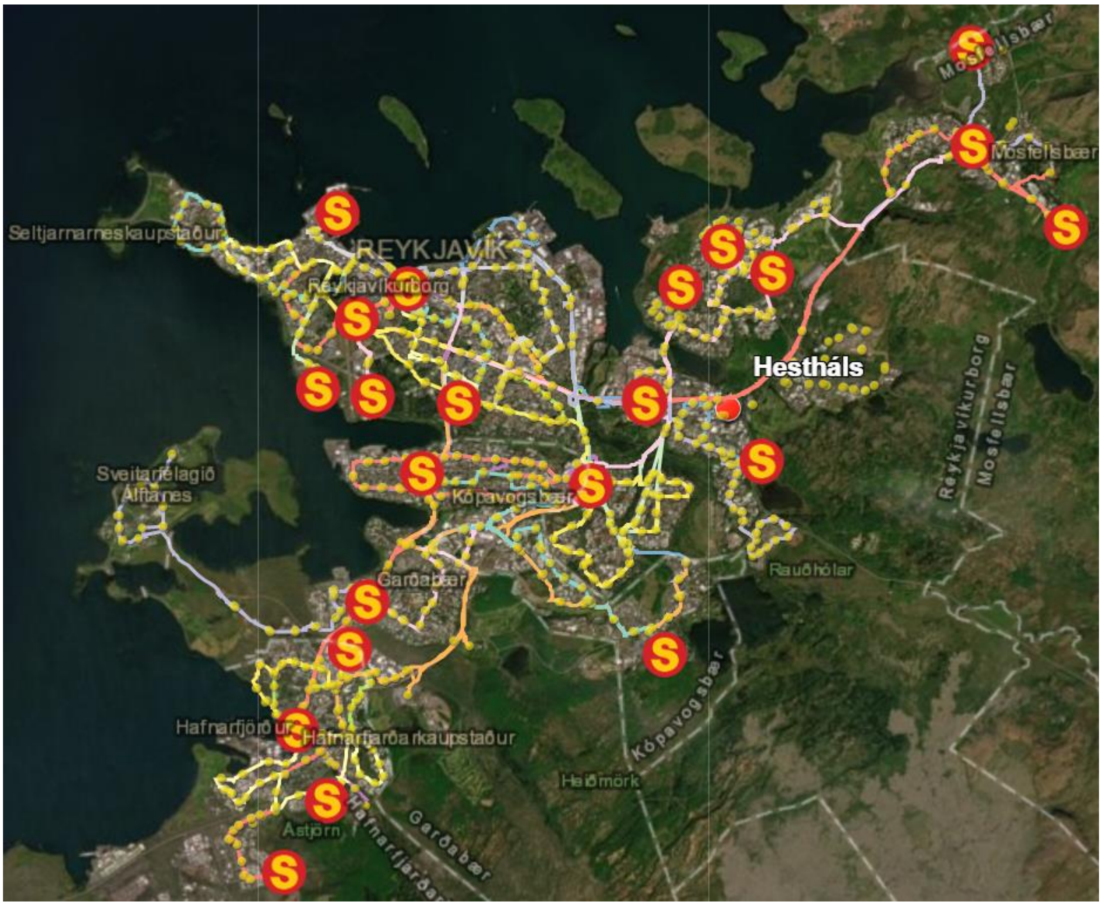


Figure 4 - Current bus network in Reykjavík

Public transport bus systems usually have a network concentrated around several hubs. Those hubs give the possibility of transferring to another line, or to another modality. Since there is no rail network in Reykjavík, there are no centralized hubs. The bus network is more spread than in most cities, as shown in Figure 4.

Strætó bs. is the bus operator in greater Reykjavik. They operate all the buses, except the bus lines that are owned by other bus operators (mostly national lines and touristic buses). About 40-45% of the bus lines in Reykjavik are put out to tender, outside Reykjavik all bus lines are put out to tender. Strætó has a depot at Hesthāls. The location is leased, but for the purpose of this study, the current depot is designated as the depot location throughout the phases.

2.2 Size of the BRT fleet

For the purpose of this study, the Borgarlína network is assumed to be implemented in three phases. To estimate the total cost of ownership, it is important to determine the size of the fleet of the network for each phase, and the amount of yearly travelled kilometers. The intended interval time, distance and trip time of every line of the Borgarlína is based on the initial concept for the new route network from November 2019. Based on those numbers the size of the fleet and yearly kilometers are shown in Table 3. The numbers are based on the use of diesel vehicles.

Phase	Line	Vehicles	Yearly km (estimate)
1	A	7	889,000
	B	7	934,000
	C	6	973,000
1/2	Strætó network	121	9,600,000
2	D	6	1,073,000
	F	6	900,000
3	E	7	1,183,000

Table 3 - Vehicles and kilometers

To calculate the number of vehicles needed for each line, the stopover and fleet reserve (buffer and maintenance) are included in the calculation. The kilometers to drive from and towards the bus depot are excluded in this calculation due to the differences between lines. Refuelling will take place within or near the depot. The estimates for each line are used as input for the TCO model. If a scenario leads to extra kilometers compared to the base scenario, the difference is described in later chapters and used in the TCO model.

The amount of kilometers per vehicle for the Borgarlína lines are higher than the average amount of kilometers per vehicle in the current situation. In the designed network, starting points are a high frequency and a high average speed. If those criteria are not met in the final network, additional vehicles might be needed to operate the Borgarlína network. The comparison in this study is based on the current starting points.

2.3 Hubs

The current network is visualized by a GiS Map. All current (red) and future (black) hubs[4], end stations and the bus depot are visualized in Figure 5.

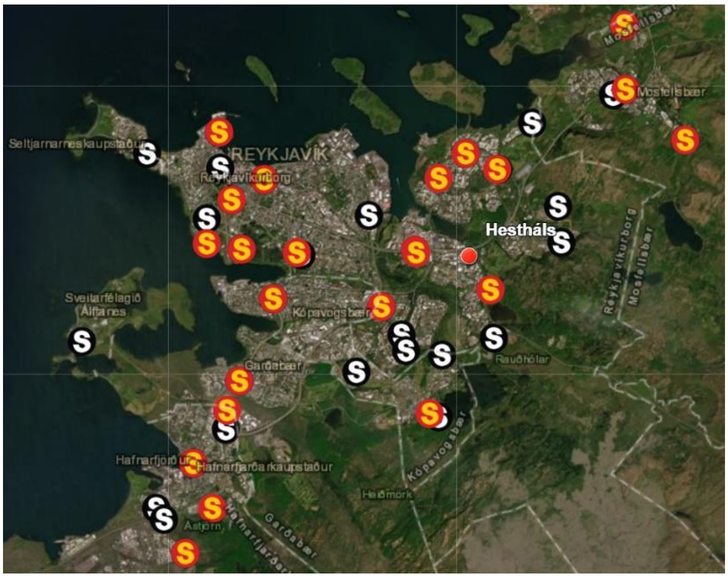


Figure 5 - hubs and end stations

A complete map, including locations of sustainable fuel infrastructure, is available online[5]. A map for each phase of this project is part of the final report and presentation.

[4] *The locations of the hubs are not final and might be sbject to change later in the project*
[5] *https://vso.maps.arcgis.com/apps/webappviewer/index.html?id=1c0d7cc776104d7cb710033e7099951c*

2.4 Sustainable infrastructure

2.4.1 Charging possibilities, electrical infrastructure

Iceland has rich resources of hydroelectric and geothermal energy, which are used responsibly and sustainably to provide electrical energy for industrial, commercial and domestic use.

There are two companies in the Reykjavik area that distribute electricity:

- Veitur Utilities (https://www.veitur.is/en) is the main electricity supplier in the capital area. Veitur´s Electricity distribution covers six municipalities in the capital area; Reykjavík, Kópavogur, Mosfellsbær, Akranes, Garðabær and Seltjarnarnes.
- Veitur Utilities distribution systems are linked to the Landsnet (https://www.landsnet.is/english/?) transmission system at three locations in the capital area: the transmission system at Korpa, Geitháls and Hnoðraholt. This is from where the electricity is imported by the high voltage cables to ten substations around the area. The substations divide the electricity via a branch system into thousand base stations (transformer stations) from where the electricity is provided to the well-known street fuse boxes. These street cabinets will provide, on their turn, energy to the so-called home-cables for the end user (HV: 11kV, LV: 400V 50Hz). See the GiS map[6] for locations of those stations.

Electrical supply and distribution in Reykjavik have been unbundled, Veitur Utilities and ON Power are subsidiaries of OR (Reykjavik Energy). Veitur Utilities is the electrical distributor and ON Power is the energy supplier.

HS Veitur (https://www.hsveitur.is/en) distributes electricity in Hafnafjörður, Álftanes and the western part of Garðabær.

Tariffs are similar for these two distributors:

Electricity prices	Veitur Utilities	HS Veitur	Units
Fixed fee	36.54	41.98	ISK/Day
Energy surcharge	7.38	7.44	ISK/kWh

Price includes 24.0% VAT[7].

The Icelandic government has announced measures to facilitate the switch to electric cars in the country. An infrastructure, making it possible to charge electric cars throughout the country, will be vastly improved. Novel charging stations will be installed by highways and at hotels all over the country. Infrastructure in the capital area for charging stations is in rapid growth and the electrification of buses should therefore fall well with the future infrastructure of Reykjavik area.

For the purpose of this study, it is assumed that the Borgarlína network will have its own infrastructure at the depot and if needed also at several hubs and/or end stations. This will be separated from the public charging point infrastructure.

2.4.2 Biogas infrastructure

Biogas is produced from waste. The production is about 2 million normal cubic meters (Nm^{3}) per year, it is supposed to increase with 3 MNm^3 in 2020-2021. After opening a new biogas and composting plant in 2025, according to Sorpa the production can be increased with an additional 3MNm^3 up to a total of 8

[6] *https://vso.maps.arcgis.com/apps/webappviewer/index.html?id=1c0d7cc776104d7cb710033e7099951c*
[7] *The VAT on electricity is calculated at 24%. However, specially measured electric heating is subject to 11% VAT*

MNm^3 per year. The biogas produced by Sorpa has been certificated according to the Nordic swan and is the only fuel with this accreditation in Iceland.

To put this into perspective: when all buses of both Borgarlína and the Strætó network are converted to Methane, roughly $13MNm^3$ is necessary per year. This is considering that lines A-F are operated by 18m buses (with a CNG consumption of 0,57 kg/km = $1{,}02m^3/km$), and the other lines with 12m buses (with a CNG consumption of 0,41 kg/km = $0{,}74m^3/km$).

The quality of the gas:

- Methane concentration (CH_4): > 95% vol, 90% of the time and always > 88% vol
- Concentration of $CO_2+O_2+N_2$: < 5% vol, 90 of the time and always < 12% vol
- Hydrogen sulphide (H_2S): < 16 ppm
- Humidity: < 3,7 mg/Nm^3
- Max pressure: 10 bar in the Methane pipeline, 240/200 bar in container
- Working pressure: 6 to 9,5 bar in the Methane pipeline
- Density: < 0,77 kg/Nm^3, 90% of the time and always < 0,79 kg/Nm^3

Iceland implemented the EU standard, EN 16723-2 (IST EN 16723-2). The quality control of the production of Methane has shown that it fulfils the highest quality (gas class 2H: Wobbe – coefficient in the range 45,7 – 54,7 MJ/m^3) over 99% of the time 2018 and 100% of the time in 2019. Class two is always fulfilled (gas class 2E: Wobbe – coefficient in the range 40,9 – 54,7 MJ/m^3)

Biogas is delivered to three oil companies: N1, Olís and Skeljungur (SHELL). N1 receives the gas via the pipeline. The pipeline is 10 km long and is 110 mm wide at 10 bars. Olís receives the biogas via high pressure demountable tank at two stations Mjódd and Álfheimar. Skeljungur receives the biogas via high pressure demountable tank at one station at Milkubraut close to Kringlan.

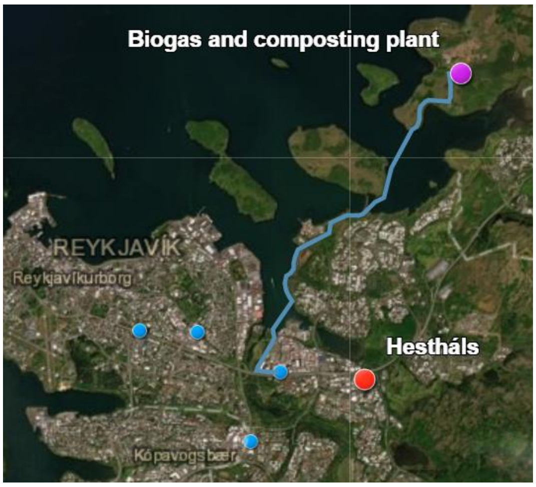


Figure 6 - Location of Methane plant, pipeline and bus depot (the blue dots are the tank stations)

2.4.3 Hydrogen infrastructure

OR (Orkuveita Reykjavíkur) has one production plant at Hellisheidi Power Plant just outside of the capital area that can produce Hydrogen. The Hydrogen plant can produce 150 Nm^3 or about 13 kg/hour at absolute maximum but production is temporarily halted.

There is another company named Carbon Recycling International (CRI) that creates renewable methanol from carbon dioxide and Hydrogen using water electrolysis or, alternatively, Hydrogen captured from industrial waste gasses[8]. CRI uses all produced Hydrogen to produce methanol that is exported since there is no domestic market. Renewable methanol can easily be combined with fossil fuels to reduce carbon gas emissions. This will not provide a fully renewable fuel system, but it may provide a short-term solution. CRI would regard a domestic market as a positive thing.

There are three Hydrogen filling stations in Iceland. One in Njarðvik (close to Keflavik airport) and one at Vesturlandsvegur (close to the Hestháls bus depot) and one at Miklabraut (close to Kringlan). None of them is currently operating due to an accident in Kjørbo Hydrogen station outside Oslo (Norway). During the investigation of this accident they will remain closed. For the purpose of this study, it is assumed that Strætó and the Borgarlína network will have its own Hydrogen filling station infrastructure at the depot.

If the fuel of choice for the Borgarlína and Strætó network will be Hydrogen, this Hydrogen will be produced by an electrolyser plant which would be built around 67km from Reykjavik. The Hydrogen production of this plant will be enough to provide the Borgarlína and Strætó buses with Hydrogen.

[8] *The technology is not used in Iceland yet.*

3 Relevant taxes and policies

To understand the feasibility of particular energy carriers, it is important to contemplate the network in the local context: fuel tax policies, spatial planning policies and environmental policies all have their own impact on the costs of the system. The current network also gives insight in the possibilities for the transition towards sustainable fuels. Not all parts of the described context will directly reflect in the calculated costs later in the study. The aim of this chapter is to describe the context of the Borgarlína network and the environment it will be part of as complete as possible.

3.1 Taxes

The current tax regime is favourable to decarbonising transportation. Actions are limited in volume and have a moratorium on special discounts by the end of 2023. Whether the current practice will be prolonged (partially or whole) is not determined yet. If certain taxes are adjusted, it will have an impact on the total cost of ownership, especially when the changes have an impact on favouring decarbonising transportation. This paragraph covers all taxes for vehicles, considering both acquisition and operations as well as fuel taxes. All excise duty is paid off the customs price which includes, besides purchase price, the transport cost and transport insurance.

The applicable taxes to all vehicles are:

- Excise duty - Vörugjald
- VAT – Virðisaukaskattur
- Registration fee – Skráningargjald
- Automotive fee – Bifreiðagjald
- Recycling fee – Úrvinnslugjald

3.1.1 Initial taxes

Excise duty (ís. Vörugjald)

Based on emissions and value of vehicle, applicable to vehicles of 3,5 tons or more.

Vörugjald/Excise duty	gr CO2/Km	Of import value (Per gram of emissions in excess of 132 g/km)
	>132	0,26%
	>145	0,24%
	>160	0,21%
	Max	30%
Comparative schedule		
	>74	0,37%
	>81	0,34%
	>90	0,31%
The difference between Vörugjald and the comparative schedule shall not exceed ISK 1.250.000		

VAT (ís. Virðisaukaskattur)

Public buses as imported from January 1st, 2020 to December 31st, 2023 and fuelled by Methane, methanol, electricity or Hydrogen pay no VAT. This is valid for new vehicles and up to 3-year-old. This exception is granted for a maximum of 120 vehicles. The general VAT is 24% of the purchase value.

Registration fee

Each vehicle is subject to registration including the purchase of two number plates. The total fee is ISK 10.260.

3.1.2 Operational or annual taxes

Automotive fee (ís. Bifreiðagjald)
To be paid January 1st and July 1st for each semi-annual payment period and upon registration. Methane fuelled vehicles in excess of 3,5 tons pay the minimum: 58.325 for each payment period. Other emitting vehicles pay ISK 2,49 per kg in excess of 3.500kg. The automotive fee does not apply for Zero Emission vehicles.

Bifreiðagjald/ Automotive fee	ISK	Notes
Baseline, semi-annual	58.325	Paid in January and July
Per kg >3.500kg	2,49	Not applicable for Methane fuelled vehicles

Recycling fee (ís. Úrvinnslugjald)
An annual fee of ISK 1.800 is paid to the Icelandic recycling fund for each vehicle for the first 15 years of use. Upon decommissioning a refund of ISK 20.000 is given.

3.1.3 Fuel taxes

Fuel is subject to various taxes all of which are applied only to volumes of fossil derived components except that VAT is applied to the whole purchasing price. For instance, an ethanol component mixed with petrol (i.e. E85) is not subject to oil taxes.

Oil Taxes

Applicable tax	Per litre [ISK]	Notes
Oil fee (Ís. Olíugjald)	64,4	
Fuel excise duty (Ís. Vörugjöld af eldsneyti)	28,75	
Special excise duty of fuel (Ís. Sérstakt Vörugjald af eldsneyti)	46,35	Unleaded gasoline/petrol
Special excise duty of fuel (Ís. Sérstakt Vörugjald af eldsneyti)	49,1	Other gasoline/petrol
All exclude non fossil origin in part or whole		

Carbon fee (ís. Kolefnisgjald)
A carbon fee is levied on all fossil fuels.

Environmental carbon tax	ISK per litre	Notes
Gasoil, diesel	11,45	
Gasoline/Petrol	10	
Fuel oil	14,1	Brennsluolía
Fossil gas and hydrocarbon gasses	12,55	per kg

Electric energy is eligible to pay a natural resource fee according to chapter two of the same law as a percentage of purchasing price, but the value is null.

Regional adjustment fee (ís. Flutningsjöfnunargjald)
These fees are meant to subsidise fuel distribution around the country.

Fee	Per litre [ISK]
Petrol	0,5
Gasoil (Ís. Gasolía)	0,75
Other oils and mixtures for ignition	0,05
Jet fuel, kerosene	0,15
Aviation fuel	0,1

VAT (ís. Virðisaukaskattur)
VAT is 24% of purchase price.

3.2 Future development

To prevent further climate change the Icelandic government is working on various programs to set action, adaption and sustainable development goals. These programs are explained underneath.

3.2.1 Ministry of Finance working groups

A working group on transportation taxes has worked at the Ministry of Finance and published a report of their findings in August 2018 and some of the suggestions have made their way towards legislation and the tax code. The report states that the goals of the work are to harmonise, simplify the tax code as well as introducing measures that conserve energy and favour domestic energy sources. This providing the state with adequate revenue. A new ad-hoc working group started recently on the same subject.

3.2.2 Iceland's climate action plan

Iceland's climate action plan for 2018-2030 has several actions on renewable fuel and public transport. An English summary of the plan is available at the government website[9].
The main emphasis of the plan is on two measures: 1) to phase out fossil fuels in transport, and 2) to increase carbon sequestration in land use, by restoration of woodlands and wetlands, revegetation and afforestation. Among measures to provide clean transportation are listed in Table 4.

A. CLEAN ENERGY TRANSFER IN TRANSPORT	
1. Tax incentives for clean cars and fuels	Iceland offers already generous temporary tax incentives for the purchase of electric cars and other clean vehicles. These incentives will expire under current regulation, but the government intends to replace them with a better calibrated longer-term system to increase the purchase of clean vehicles.
3. Support for infrastructure for electric cars and other clean vehicles	The government has allocated 210 million ISK in the years 2016- 2018 to support the build-up of charging stations for electric cars. There are future plans that government support will be increased, and also extended to infrastructure for other types of clean energy and fuels, such as Hydrogen and Methane. The support will be based on a need's analysis, by identifying bottlenecks and opportunities in consultation with local governments, rental car operators etc.
4. Building and spatial planning rules – changes to support electric cars	Regulations will be reviewed to ensure that new buildings will be designed allowing the infrastructure for charging electric cars.
7. Improved use of Methane from landfills	Methane is collected from gas emissions from two landfills in Iceland, and part of it is sold as fuel for vehicles. Opportunities to increase landfill gas collection and the use of Methane will be charted.
9. Domestic fuel production from biomass and waste	A thorough analysis will be made on the possibilities of producing fuel from biomass and waste in Iceland. Such possibilities include rapeseed

[9] https://www.government.is/lisalib/getfile.aspx?itemid=5b3c6c45-f326-11e8-942f-005056bc4d74

	oil production, using plastic waste and offal. Pilot projects in all these fields have been conducted, but a comprehensive study is lacking. Current regulations may be a bottleneck for fuel production from waste and will be reviewed.
10. Support for public transport and shared services in transport	The government will promote public transport by supporting infrastructure development (transport hubs, priority lanes etc.) and reviewing regulation that might support shared services in transport and other innovative solutions.

Table 4 - Iceland's Climate Action Plan for 2018-2030. Actions relevant for the project are listed in the table[10]

3.2.3 Report from the Ministries' Working Group on energy clean energy transition in transport

Governmental actions to follow up the Iceland's Climate Action Plan for 2018-2030 are e.g. support for clean fuel infrastructure[11]. In 2019 support was aimed at electrical fast-charging stations. In 2020 the government will grant 200 million ISK for the following projects, through the Energy Research Fund:

- Infrastructure for renewable energy (electricity, Methane, etc.) for fleet managers (public transport, buses, shuttles and other fleets of vehicles) – 100 million ISK
- Electric infrastructure for harbours – 70 million ISK
- Infrastructure for e-vehicles at restaurants and hotels – 30 million ISK

The decision for allocation of funding is based on a report from the Green Energy Cluster[12]. Additional actions are suggested and the government states that those suggestions will be considered later. The main barriers for implementing clean fuel for buses are identified as lack of market supply of clean energy buses and high investment costs. As today Methane buses are fuelled at public fuel stations, which is inconvenient. Charging/refuelling hubs for public transport are mentioned as a solution.

3.2.4 Directives, regulations and the Paris Agreement

Iceland is in the European Economic Area (EEA). EU directives and regulation on transport, environment and energy are generally implemented without adaptions. Several exceptions are made regarding energy efficiency for buildings. Iceland signed the Paris Agreement with the European Union and needs to reduce its greenhouse emissions by 29% (based on 2005 levels) by 2030.

In 2008, improvement of local air quality and reduction of noise pollution became important goals for the EU and its members, as stated in the Directive on Ambient Air Quality and Cleaner Air for Europe. With the introduction of the EURO VI standard for buses, significant improvements for reducing local emissions have been reached; however, it is still not possible to avoid such emissions.

3.2.5 Comparison of countries and regions on zero-emission buses

Projects have been initiated all over the world. For example in India, Korea, China, Japan, South Africa and Europe. Recent announcements of leading public transport authorities indicate a much stronger push for alternatively fuelled buses over the next years.

[10] https://www.stjornarradid.is/verkefni/umhverfi-og-natturuvernd/loftslagsmal/adgerdaaaetlun/
[11] https://www.stjornarradid.is/lisalib/getfile.aspx?itemid=28f7220b-4994-11ea-9454-005056bc530c

[12] https://www.stjornarradid.is/lisalib/getfile.aspx?itemid=0094efa6-4994-11ea-9454-005056bc530c

Based on European legislation, national public procurement targets for clean buses will range from 24% to 45% in 2025, and from 33% and 66% in 2030 – depending on a country's population and GDP[13]. This means almost a quarter of new public buses in Germany and Sweden should be zero-emission by 2025 – i.e electric. Other EU countries with a lower GDP will see more gradual growth: almost a fifth of new public buses should be zero emissions by 2030. Also, other countries are investing in zero emission buses.

Cities of Athens, Paris and Madrid plan to remove diesel vehicles by 2025, as well as the government of Norway. Other cities and regions have announced plans to stop purchasing conventionally fuelled buses, including Copenhagen (in place since 2014), London (announced for 2018), Berlin (announced for 2020) or Oslo (announced for 2020)[14].

In the Netherlands, by 2030, all public transport buses are required to be zero-emission, and the Dutch provinces committed to only buy zero-emission buses from 2025 onwards. This is agreed upon in the Dutch Climate Agreement (June 2019). In the Netherlands there are about 500 zero-emission buses at the moment, including Hydrogen (FCEV) and electric (BEV). This is mainly concentrated in the provinces Groningen, Drenthe and Zuid-Holland. In Groningen and Drenthe this is 47% of the total amount of buses.

There are a couple of manufacturers leading in the market. Manufacturers (in 2019), from the 770 zero-emission buses in the Netherlands:

- VDL: 486
- Ebusco: 109
- Heuliez: 49
- BYD: 44

Transport companies in the Netherlands have already ordered almost over 1000 zero-emission buses after 2021. The amount of refuelling stations is expected to increase from 8 to 20 by 2022.

[13] https://www.transportenvironment.org/press/eu-deal-will-see-roll-out-cleaner-public-buses-faster-uptake-zero-emission-technology-needed
[14] https://ec.europa.eu/transport/themes/urban/cleanbus_en

4 Assessment of the different propulsion methods

4.1 Overview

Each fuel system has its own impact on the environment, and its own advantages and challenges. Table 5 shows a qualitative description of the properties of each fuel system.

	BEV (electric)	FCEV (Hydrogen)	Natural gas (CNG/LNG/Bio)
Advantages	• Zero-emission and air quality[15] • No safety risks due to explosive atmospheres • Noise reductions if compared to ICE on diesel fuel	• Zero-emission and air quality • Short refuelling time • Less weight if compared to ICE and BEV • Lower material footprint • Suitable for long distances • Less costs for personnel • Noise reductions if compared to ICE on diesel fuel	• Close-to-zero PM emissions and less NOx if compared to ICE on diesel fuel • Flexible in use • Suitable for long distances • Small noise reductions if compared to ICE on diesel fuel
Main challenges	• Limited vehicle range, especially when cold • Frequent charging needed, which takes time and has an influence on operations • Heavy charging infrastructure needed • Weight of the battery • Use of scarce resources for the battery (social and geopolitical risks) • Limited lifetime of batteries • Increased fire safety risks in charging stations and in the vehicle	• Hydrogen is only 'green' if produced by electrolysis, powered by green electricity. (Worldwide most Hydrogen is produced out of Methane) • Low utilisation of tank station (adds up infrastructural costs) • Production costs of Hydrogen are high (in general for both CAPEX and OPEX and previous bullets will add costs) • Energetic losses in production, transmission and storage are higher compared to BEV • Increased safety risks due to explosive atmospheres • Limited lifetime of fuel cells	• CNG / LNG are still emitting CO2, not "zero-emission" • Caloric value of biogas may differ in time • Contaminations in the biogas may lead to unwanted emissions • Gas treatment installations reduce the total energy efficiency of the transport system • Possibility of Methane slip in production, transportation and consumption of Methane
Availability vehicle	• Batteries have become more efficient and have larger capacity (now up to 525 kWh) • Availability has been improved in recent years • Maintainability has been approved	• Installed base is still limited (many pilots ongoing but the number of full-scale projects in operation is still limited) • There are currently no manufacturers that produce 24 meter fuel cell buses, but new models are expected from major manufacturers	• 'Off the shelf' vehicles with proven technology • Contaminations in the biogas may lead to extra maintenance demands
Availability infrastructure	• The capacity of the electricity grid may be limited • Overnight and/or OC (opportunity charging) required	• Fenced area is required for fuel storage and treatment • Safety area and restricted area around the fuel storage are required	• Existing infrastructure may be used, this depending on gas composition and possible contaminations in the gas

[15] *With exception of buses with diesel heaters*

Future development until 2030	• Innovations in battery technologies will take place • Battery: <= 1.000 euro per kWh (max ca 500 kWh) • More competitive costs of opportunity chargers will appear • More uniformity in charging infrastructure • Better end-of-lifetime perspectives for batteries	• Innovations in fuel cell technology will take place • Costs of Fuel Cells will get more competitive • With other applications for Hydrogen the availability will increase	

Table 5 - Qualitative description of the impact of each fuel system

4.2 Battery-powered Electric Vehicles (BEV)

4.2.1 Market review

“Urban buses are one of the great success stories of rapid EV market uptake. Leveraging the suitability of their fixed routes and schedules, their frequent stops and municipalities’ ambitions to reduce local air pollution, as well as the longer-term investment portfolios of (certain) municipal fleet managers, a market for electric buses emerged quickly.” (Source: Tracking transport report IEA)

Based on the numbers of new registrations (EAFO), it can be concluded that BEV buses stepped in with a significant amount in 2016. According to the Global EV Outlook 2019 (IEA), the amount of BEV and PHEV buses continues to grow rapidly and can save up to 50.7 Mt CO_2.

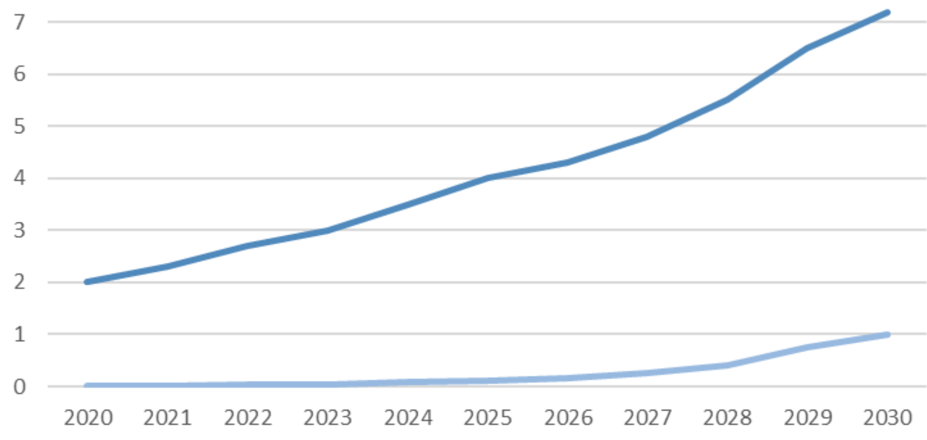


Figure 7 - Growth of BEV and PHEV buses until 2030 (in million vehicles worldwide)

Electricity is a fuel widely used for public transport. Current Life Cycle Analysis of battery packs however show poor outcomes. The materials used in the battery packs partly come from the mining industry in Congo (cobalt) and Chile (lithium). The mining industry there leads to social and political problems and the industry is not sustainable. The lifetime of the battery packs (circa 7 years) is far less than the lifetime of the rolling stock (circa 10-15 years). The end-of-life perspectives of present battery packs are currently unknown.

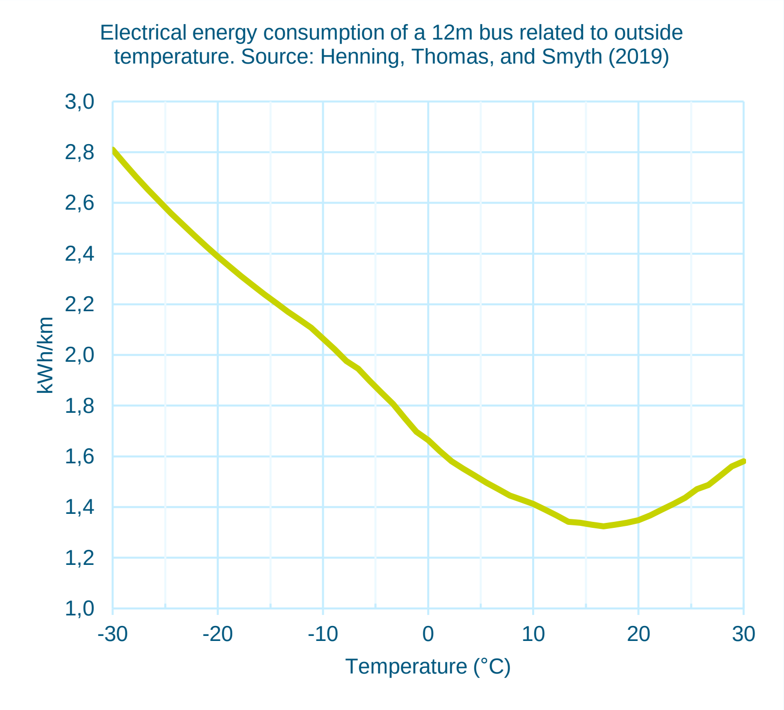
BEV buses are widely available, both ready for opportunity charging and plug-in charged. Plug-in charged buses with diesel heaters are also widely available, but so far manufacturers don’t allow biodiesel (B100) to be used. For the purpose of this study, it is assumed that for a big order, permission can be negotiated.

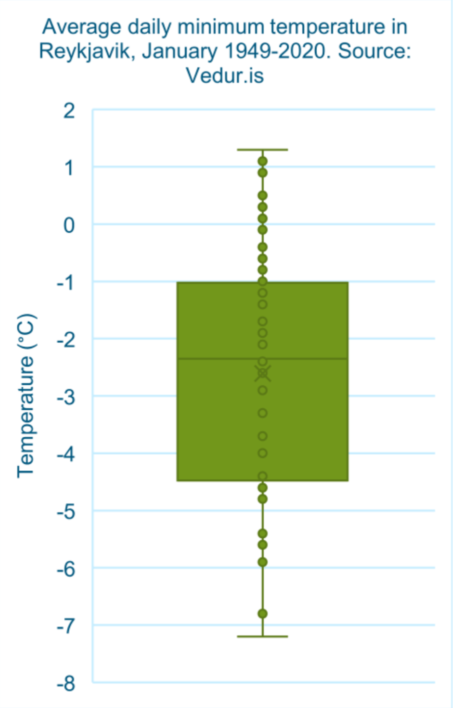
4.2.2 Driving range

The two challenges regarding BEV buses are the driving range and the fact that it needs to charge, which takes longer compared to refuelling diesel. The critical range[16] of BEV buses currently in operation varies between 100 and 200 km, when heated by electricity. Buses heated by diesel have a higher critical range. Since battery and vehicle technology is developing quite fast, newer bus models have an improved range. This year, buses with a range of 200 km will be implemented in Hamburg. Expectations are that battery efficiency (the amount of kWh's stored per kg battery) will increase even more over time, so that the range of the buses increases, especially with buses making use of opportunity charging.

The exact range of the bus hugely depends on the weather conditions (amongst other variables such as wind speed, number of stops, average speed, hills and driver style). This is partly because the battery needs to be heated or cooled, and partly because the passenger compartment needs to be heated in winter. Some bus models have a separate (diesel) heater to heat the battery and/or the passenger compartment. This is for example the case with the Yutong buses currently in operation with Strætó. These Yutong buses are diesel heated and have a fuel consumption in winter conditions of around 1,2 kWh per kilometer. Since sustainability is key for the Borgarlína network, we assume that the new to be deployed vehicles will be heated by electricity. To make a fair comparison however, a TCO calculation is made for both diesel heated and electricity heated buses.

Winter conditions in Iceland may have negative effects on the range of battery-powered vehicles. The electricity consumption of buses which are also heated by electricity is shown in the graph, related to temperature.





The charging infrastructure needs to be designed to critical circumstances, to the worst-case scenario. In January, the coldest month of the year, the 75% percentile of the minimum temperature per day is -4,5 °C, as shown in the boxplot. The electricity consumption of a 12m electric bus with that temperature is 1,9

[16] *The driving range during winter conditions*

kWh/km. Since the Borgarlína will be operated with 18m buses, the weight of these vehicles is much higher, and so is the electricity consumption. For 18m buses the electricity consumption will be about 2,8kWh/km in critical conditions, since the buses are heavier. That will be the critical energy usage the calculations will be made with.

In the future, batteries will develop further. The power density of the batteries will increase. This means that more electricity can be stored in lighter batteries. However, no accurate data can be provided on these developments. Therefore, we assume that the development of batteries for opportunity charged buses (in terms of kWh/kg battery) will increase with half the speed with which it has developed in the past ten years. This estimation is conservative, to not overestimate the speed of development. The buses used for opportunity charging generally have a smaller battery capacity then plug-in buses but are able to charge faster.

The need for electrical infrastructure will be modelled according to the critical capacity of the electrical buses as described in Table 6 and Table 7. Furthermore, we assume charging speeds at the depot of 50kW, and we assume that the buses in operation are able to charge with 300kW at Opportunity Chargers on strategic locations in the city. These charging speeds are based on specifications of currently available buses and chargers.

Phase	12m bus			18m bus		
	Usable battery capacity (kWh)	Critical electricity consumption (kWh/km)	Critical driving range (km)	Battery capacity (kWh)	Critical electricity consumption (kWh/km)	Critical driving range (km)
1 (2024)	350	1,9	184	350	2,8	125
2 (2029)	400	1,7	236	400	2,5	160
3 (2034)	450	1,6	288	450	2,3	196

Table 6 - Critical electrical capacity (opportunity charging)

If the electric buses are heated with a diesel heater, the driving range of the buses will increase. The diesel consumption for auxiliary heating systems is 4 l/hr[17] when fully used. In the Icelandic climate the average year-round consumption is around 3 l/hr.

Heating	12m bus			18m bus		
	Usable battery capacity (kWh)	Critical electricity consumption (kWh/km)	Critical driving range (km)	Battery capacity (kWh)	Critical electricity consumption (kWh/km)	Critical driving range (km)
Electric	500	1,8	278	500	2,3	217
Diesel	525	1,3	404	525	1,8	291

Table 7 - Critical electric capacity (Plug-in charging)

4.2.3 Charging aspects

Electrical buses can be charged overnight (Overnight Charging), and during operations during the day (Opportunity Charging). Overnight charging is almost a boundary condition: a bus needs to leave the depot in the morning being fully charged. When the distance per day exceeds the range of the bus, opportunity charging is necessary. The characteristics of the Borgarlína network show that the buses drive up to or

[17] https://www.valeo-thermalbus.com/eu_en/Products/Heating-systems/Thermo-E-plus and https://www.eberspaecher.com/en/products/fuel-operated-heaters/product-portfolio/water-heaters/products.html

exceeding 400 km a day. This means that the buses need to charge during the night as well as during the day.

Figure 8 – Overnight Charging station at the depot, Municipality of Dordrecht, the Netherlands

Impact on operations

To charge buses during the day, they can either drive back to the depot and charge there, or charge on strategic locations during layover on a central hub, for example on the BSÍ bus terminal.

Two charging strategies can be distinguished to charge public transport buses during the day:

1. Charge after each round trip. This needs a sufficient layover time and a strict timetable. With a charging speed of 300kW, when the bus has a layover time of 10 minutes, it can charge around 20-30km of driving range (dependent of the weather and the length of the bus). With an average trip length of 33km (around, so from the terminal back to the terminal), these 10 minutes of fast charging is almost enough to charge the amount of kWh's needed for one round trip. But when the bus is delayed and the layover time decreases, there is not enough time available to charge all energy which is just consumed. This means that the battery gets emptier and emptier during the day.
2. Continue driving until the battery is almost empty, and then charge for a longer period. This means that the bus does not charge after every ride, but that it makes as many round trips in succession as possible. If the battery falls below 40 km range, the bus is removed from the timetable and charges for a longer period. It takes about 40 minutes to sufficiently charge the bus for the remaining hours.
   This can be done at the depot, which means that the bus has to drive back there, and charge with lower speeds (typically 50kW). This means that more buses need to be deployed, since a bus is out of operation during the day. It can also be done using Opportunity Chargers at the layover location. Then charging takes less time. Both these two scenarios are elaborated in the TCO calculations.

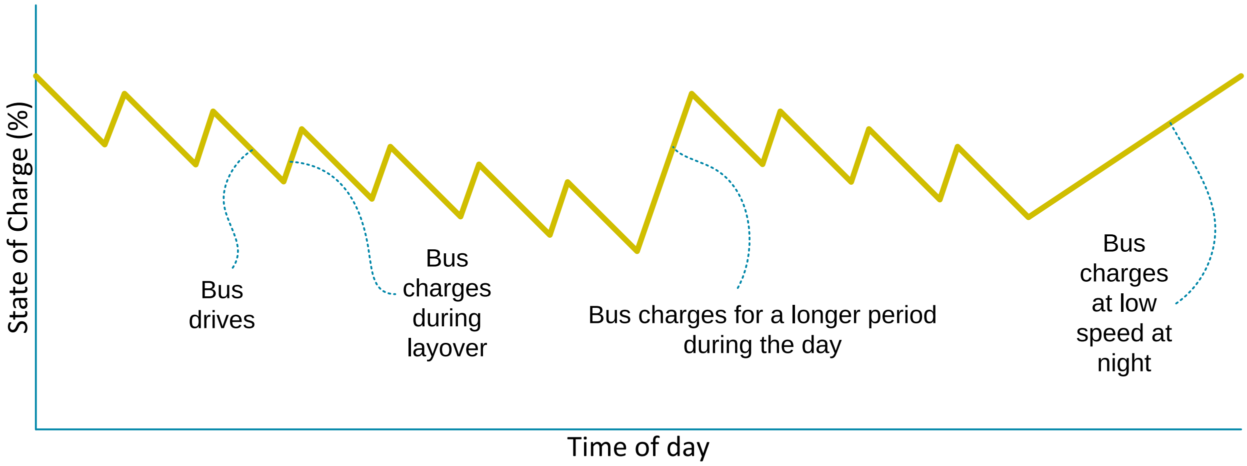


Figure 9 - Schematic representation of the State of Charge of a bus during the day, when charging during layovers, during off-peak hours and during night

For the Borgarlína network a hybrid charging system combining these two charging methods will be necessary. During the day, outside of peak hours, when layover times are longer, the layover time at certain hubs can be used. And when a bus slowly runs out of driving range, it needs to charge for a longer period. A schematic representation of this charging method is shown in Figure 9.

Scenario with Opportunity Chargers

Every line needs at least one location with several opportunity chargers, and it means that more buses need to be deployed than when powered by Hydrogen or Methane, since the buses will be charging for around 40 minutes once a day., This means more buses are needed to run the time schedule.

The number of chargers necessary is calculated assuming the critical conditions where energy consumption is highest. It is calculated by determining the amount of buses per line which need to charge at the same time, to be able to drive all day.

The best location to place the opportunity chargers is at a hub where multiple lines intersect, and ample space is available. The reasons for that are:

- The more charging infrastructure is spread across multiple locations, the more chargers are needed because chargers can no longer be used by different lines
- Buffering and charging at a central hub enables Strætó to exchange drivers and buses between different lines. This is not possible if the buffer and charging time of the buses is on the endpoint of the line. Strætó thus loses control space to organize operations as robust as possible
- Endpoints of lines might shift in the future. Lines for example are extended or end at a different destination. In that case, the charging infrastructure is suddenly in the wrong place.

With the battery size and energy consumption as stated in this paragraph, the number of chargers needed per line are determined per phase in Table 8.

Phase	BSI Terminal		Hlemmur		t.b.d.	
	Chargers	Lines	Chargers	Lines	Chargers	Lines
2024	9	A, C	5	B	12	25% Strætó
2029	13	A, C, F	10	B, D	36	100% Strætó
2034	13	A, C, F	14	B, D, E	36	100% Strætó

Table 8 - Chargers per phase

For the Borgarlína network, it seems that Hlemmur and the BSI Terminal both are logical locations to place charging infrastructure. For the Strætó network, good charging locations need to be determined. Depending on the line configuration, these locations might also be Hlemmur and/or BSI, amongs others.

The high number of chargers needed at a hub causes a severe spatial impact. On the terrain of the BSI terminal, there is enough space available to build all necessary facilities. At Hlemmur the available space is limited. Figure 10 shows an exemplary lay-out for electrical charging infrastructure at Hlemmur.

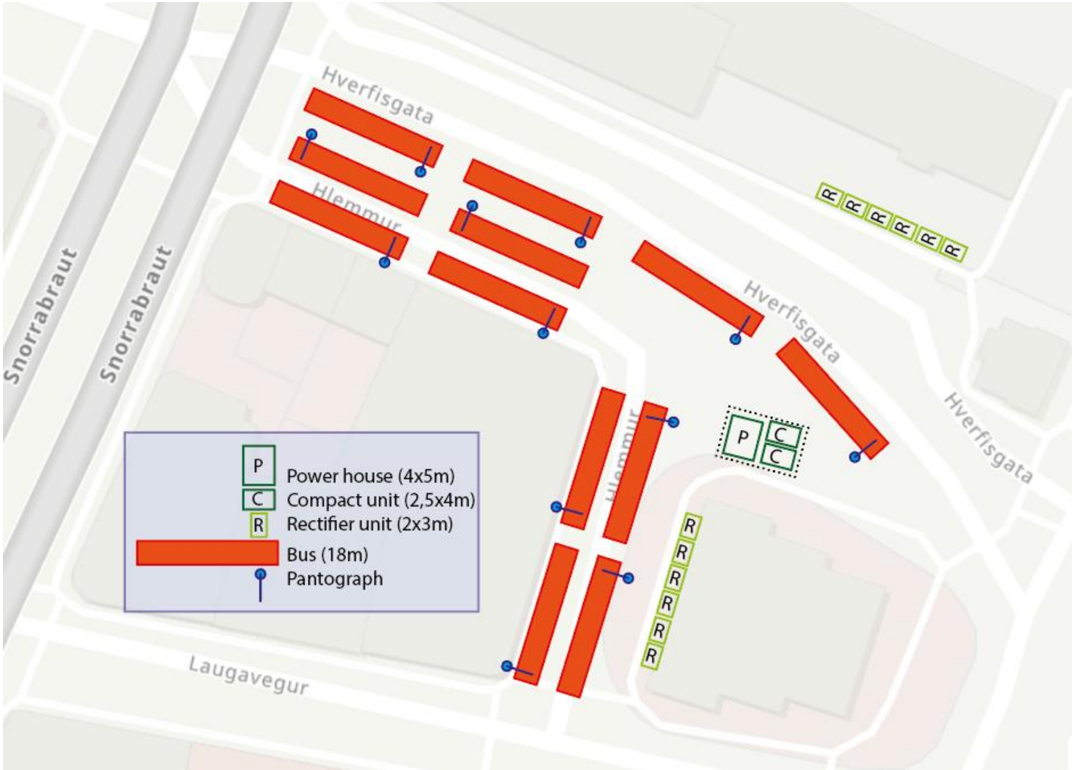


Figure 10 - Charging facilities at Hlemmur

Within the current lay-out, Hlemmur can facilitate 12 buses (18m) at the same time. There is also enough space available for all charging equipment. However in phase 3, Hlemmur needs to be able to facilitate 14 charging buses at the same time. Hlemmur needs to be redeveloped as hub in order to accommodate the Borgarlína lines in phase 3, especially since Hlemmur will also still be in use for the regular Stræto network. Another option is to redesign the public transport network and create other hubs.

Scenario without Opportunity Chargers

In the TCO model, a scenario without opportunity charging is considered as well. This means that the only charging location for the buses is at the depot. To be able to operate the Borgarlína and Strætó network with these buses, different buses can be deployed: buses which don't need the functionality to charge with 300kW, but with a range which is as large as possible. The buses with the nowadays largest battery packs have a capacity of 525 kWh, which enables an 18m bus in critical conditions to drive 180 km. This means that the buses need to return to the depot once per day to charge for an extended period. The buses are used during the morning peak, and after this peak, all deployed buses need to return to the depot to charge and these buses are not available for 3-5 hours (assuming a charging speed of 50kW). After charging these buses are again available during the evening peak again. Conclusion: According to the provided frequencies of the Borgarlína system, extra buses are necessary to drive in the period between the morning and the evening peak. These extra buses are scheduled between 9:00 and 14:30, when the frequencies of the Borgarlína lines are lowered and afterwards they return to the depot to charge. At that time the buses that were deployed during the morning peak are fully charged, and these can be deployed in the evening peak. In this scenario, extra kilometers (from and to the depot during the day) and extra buses need to be taken into account.

If the electric buses make use of a diesel heater, the driving range is sufficient for the service during the day. Only a few extra 18 meter buses are needed to compensate for the length on the Borgarlína routes.

Line	Diesel	Opportunity Charging	Plug-in charging	Plug-in charging (diesel heated)
A	7	8	10	7
B	7	8	10	8
C	6	7	10	6
D	6	7	10	7
E	7	8	11	7
F	6	6	9	6
Strætó	121	139	157	121
Total	**160**	**183**	**217**	**162**

Table 9 - Number of vehicles in electric scenarios (with diesel as reference values)

4.2.4 Required infrastructure

Opportunity charging is expensive, because heavy electrical equipment is needed. Overnight charging takes place at a charging power of 50 up to 100kW, while opportunity charging requires 300 up to 400kW. Higher power means a heavier grid connection, and larger transformers. Opportunity charging buses have a big demand on the public space, caused by the combination of a HV connection, power transformer, rectifier and control cabinets and the actual charging stations.

Overnight charging at the depot

Maintenance buildings or overnight hangars might be needed at the depot(s). This should prevent low battery temperatures that reduce the operational range of the vehicles and enables the operator to pre-condition the buses which increases range and durability of the vehicles.

Recommendations to the depot infrastructure:

- Depot building or hangar space with:
    - Ample space for a dry storage of all buses that are needed for the start-up of the daily operations
    - Building utilities that prevent battery temperatures to run below 10°C
    - Electric power supply:
        - One or two incoming feeders from the public HV-network
        - One or two electrical power transformers (10/0,4 kV) and associated switchgear
        - LV power supply to building utilities
        - Connections to lightning and surge protection
        - Slow charging loading equipment with power outlets (DC) (CHAdeMO, CCS1 or CCS2 / IEC 61851-23 type)

Opportunity charging at hubs

Typical arrangement for an Opportunity Charging hub to be able to charge up to 14 buses will be:

- Concrete or similar powerhouse with:
  - High Voltage cables from the public HV-network
  - High Voltage switchboard(s)
  - One or two electric compact units, each with:
    - Incoming HV cable from the powerhouse
    - Electrical power transformer (10/0,4 kV)
    - LV switchboard with outgoing feeders to rectifier units
  - Rectifier units for each charger, each with:
    - Incoming LV cable from a LV switchboard
    - Power electronics to convert AC to DC and to protect outgoing feeder cables
    - Opportunity charging control equipment
- Power delivery area:
  - DC power cables in PVC PE protective tubes
  - Control cables and grounding cables (PE)
  - DC Connector type charging units, off-the-shelf charging poles or one or more overhead steel structure with charging connectors on multiple positions
  - Lighting equipment
  - Fencing, roadwork, support structures and other civil works associated with the loading hub

Typical surface demand for an Opportunity Charging hub will be:

- Concrete or similar powerhouse: 4 x 5 m
- One or two electric compact units: 2,5 x 4 m each
- Rectifier units: 2 x 3 m each

Safety requirements:

- Basic safety requirements to the Electrical Safety are given in the international standards EN 50110, EN 50522 and IEC 61936
- Basic safety requirements to the Fire Safety are given in the international standards EN 1363, EN 54 and EN 12464
- Based on these safety requirements, it is recommended to install the electric compact units and the rectifier units in a fenced area of a least 50 m2
- The fenced area shall be accessible for qualified service personnel only

Figure 11 - Examples of electrical equipment for opportunity charging (Amsterdam-Sloterdijk)
From left to right: Powerhouse, compact unit, rectifier units, overhead charger

4.2.5 Currently available infrastructure

At the moment Strætó operates 15 Yutong electrical buses. These buses are charged in the open air by overnight charging at the depot. This is done by 10 charging sockets of 150kW each, and the total available power for all sockets is 750kW.

Figure 12 - Depot charging

4.3 Fuel Cell powered Electric Vehicles (FCEV)

4.3.1 Market review

The application of Hydrogen requires fuel cells to power electric drives. Worldwide, the amount of fuel cell powered electric vehicles (FCEV) is growing rapidly. In Korea a public– private partnership aims to deploy 1,000 fuel cell electric buses by 2022. Korea has stated a target of 40,000 by 2040 (Study Task Force, 2019). Korea's natural gas-powered bus fleet has 26,000 vehicles, all of which could be converted to Hydrogen.

The hydrogen technology used in buses, uses the same engine as electric technology. The difference is that fuel cell technology uses a smaller battery and fuel cells. The amount of hydrogens buses in use is not comparable with electric buses yet but scales up rapidly. Pilot use all over Europe helps in terms of development, some of which are already running over 5 years. The perspective of hydrogen has been researched intensively by the European Union[18]. Since the scope of the Borgarlína project goes beyond 2034, those perspectives are taken into account.

H2BUS and JIVE2

A new initiative called H2Bus has created a proposition in a consortium of European partners. The aim of the consortium is to scale up the number of buses and therefore be able to buy cheaply Hydrogen buses (around 375000 euros) and fuel (5 euros per kilogram Hydrogen) by 2024. It has been calculated that, by then, the Total Cost of Ownership remains only 20% higher than diesel.

The drawback is that in most countries the production of Hydrogen is done with limited use of sustainable sources. The costs of producing 'green' are higher. This is not the case in Iceland, since the Hydrogen used for buses will be produced by electrolysis, a technique where electricity is used to produce Hydrogen. This electricity is produced by a hydropower plant, and thus zero-emission. The electricity and Hydrogen prices in Iceland are also significantly lower than in most European countries.

Example: The Netherlands

There are multiple Dutch bus manufacturers with a relevant market position (for example VDL, DAF and Holthausen). The public transport organisations in Groningen, Drenthe and Zuid-Holland have been a frontrunner in Hydrogen buses. In November 2019 the state secretary declared that 50 new Hydrogen buses will be added to the fleet in 2020, of which 20 buses for the province of Groningen.

4.3.2 Required Infrastructure

Fuel cells in electric vehicles for public transport require Hydrogen[19] as their source of energy. When delivered to the vehicle the Hydrogen is gaseous. Differently from well-known (fossil) fuels, small H_2 molecules can penetrate through most synthetic polymers and subsequently create explosive atmospheres in combination with air (the small H_2 molecules are lighter than air). European directives are applicable to reduce the potential risks that come with the transport, storage, delivery and use of Hydrogen. Compliance to these directives will reduce the risks of Hydrogen considerably.

The Strætó and Borgarlina buses can be refueled once a day, at the depots. Options for the delivery of Hydrogen at the centrally located Hydrogen Refuelling Station:

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[18] https://ec.europa.eu/commission/presscorner/detail/en/FS_20_1296
[19] Previous experiments with Hydrogen to formic acid conversions did not lead to for transport applications. Applicable formic acid applications are currently in mobile power generators only
Source: https://dens.one/our-products/

1. **Transport of gaseous Hydrogen by road**
   Hydrogen can be transported by road as compressed gaseous Hydrogen. But under standard conditions it has low density (0.0899 kg per Nm3). Therefore, the transport is less efficient than for liquid fuels (like petrol or diesel). To increase the density, the pressure is increased. This requires pressurized gas cylinders for transport and storage (tubes, bundled together inside a protective frame). The tubes themselves are usually made of steel and have a high net weight. In doing so, the transport of gaseous Hydrogen is not very efficient. The supply to the new public transport network would require several extra vehicle movements (with gasses at a high pressure) in between the production location and the capital area.
2. **Transport of liquid Hydrogen by road**
   Hydrogen can also be transported by road as a compressed liquid. Over longer distances it is usually more cost-effective to transport Hydrogen in liquid form. As a liquid, the working pressure[20] is 4 to 8 bar (400 to 800 kPa). Transport can be done by lorry. But for these lorries the use of tunnels, bridges or similar infrastructure may be limited or prohibited[21].

Recommendations to the depot infrastructure:

- Endpoint building(s) or hangar(s) with:
  - Semi-open space or vehicle maintenance room with ample ventilation to prevent explosive atmospheres in all overnight storage locations for FECV buses
  - Connections to lightning and surge protection
  - Electronic LEL-detection equipment[22] inside these locations
  - Ex-D enclosed lighting equipment[23]
- Supply area:
  - Liquid gas supply hose, mounted on flange with primary valve and pressure release valve
  - Fencing, roadwork and other civil works associated with the delivery area
  - Ex-D enclosed lighting equipment
- Fenced area or for the local storage of liquid Hydrogen:
  - Located adjacent to the supply of liquid Hydrogen (= logistics area)
  - Sea transport container or similar prefabricated housing
  - Valves and pipes, fluid Hydrogen pump, vaporiser, (intermediate) gas storage tanks, gas compressor, gas cooler, gas purifier, gas temperature transmitters, and gas pressure governors
  - Lightning conductors, earth potential bonding and surge protection
  - Ex-D enclosed lighting equipment
- Delivery area:
  - Gas dispenser with flow transmitter
  - Gas hose with breakaway coupling
  - Ex-D enclosed lighting equipment
  - Fencing, roadwork, support structures and other civil works associated with the delivery area

Typical surface demand for all depots of FCEV buses:

- Semi-open space or maintenance room: 500 < x < 2000 m2
- Supply area (open air): 50 < x < 80 m2
- Fenced area (open air): 20 < x < 40 m2
- Delivery area (open air): 100 < x < 1000 m2

[20] Publicatiereeks Gevaarlijke Stoffen 35; versie 1.0 (april 2015)
[21] The presence of a liquid fuels may result in high risks to fire fighters as a BLEVE may occur (BLEVE = Boiling Liquid Expanding Vapour Explosion)
[22] LEL = Lower Explosion Limit
[23] In accordance with the standards EN 60079-1 or IEC 60079-1

Figure 13 – Hydrogen fuel station with electrolyser (source: Bastiaan Knoors / RHDHV)

Safety requirements:

- Basic safety requirements on the storage and the transport of liquid Hydrogen are given in the European Directives 1997/23/EC (Pressure Equipment Directive), the 1999/36/EG (Transport Pressure Equipment Directive or TPED) and in 94/55/EG, revised by 2003/29/EG (Transport of Dangerous Goods Directive or ADR);
- Basic safety requirements to explosive atmospheres are detailed in the European Directives 1994/09/EC (also known as 'ATEX 95' or the 'ATEX Equipment Directive') in the 1999/92/EC (also known as 'ATEX 137' or the 'ATEX Workplace Directive') and in the 2009/142/EC (European Gas Appliances Directive).
- Basic safety requirements to the Electrical Safety are detailed in the international standards EN 50110, EN 50522 and IEC 61936;
- For safety purposes, the fenced area shall be accessible for qualified service personnel only.

4.3.3 Impact on operations

Since, a Hydrogen powered bus has an average range of around 400 km it needs to refuel at the beginning of each day and during the day if this range is exceeded[24]. We can assume that the Hydrogen refuelling station will be located at the depot. Should refuelling during the day be required, current expectations are that this can be incorporated in the time schedule of the buses. In this case refuelling barely affects operation of the buses, and no extra buses are needed.

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[24] *Current data of the Borgarlína line estimates the ranges within 310-335 km per day, and this can be done without refuelling*

4.4 Internal Combustion Engines (ICE) using CNG or CBG

4.4.1 Market review

Quote of the Transport Authority Amsterdam

"There are economic chances on fuel production. Regional produced green gas originated from biomass waste sources, like organic waste and industrial or agriculture remains, in which there are a lot of opportunities in the region of Amsterdam, can be used in the regional public transport and replace fossil fuels, mostly from oversea production. This stimulates the 'local-for-local' circular economy. Some types of bio diesel, like from recycled used frying oil as used at Biodiesel Amsterdam, have the same advantages."

The same economical chances may also be applicable to the situation in greater Reykjavik, where the Methane will be obtained from the Sorpa plant, which produces Methane out of a landfill and a composting plant. Therefore, the application of compressed natural gas (CNG) or compressed biogas (CBG) will be taken into consideration.

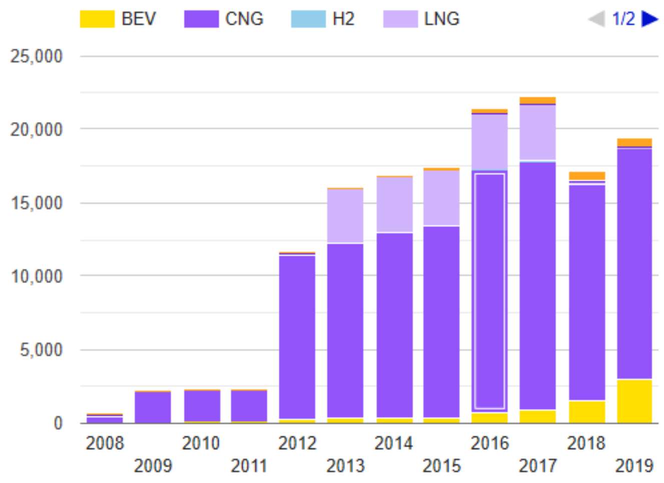

Figure 14 - Total fleet on alternative fuels in the EU (EAFO)

4.4.2 Required infrastructure

In general, 'natural gas' is composed of Methane, Hydrogen sulphide, nitrogen, carbon dioxide, water vapour and other gasses. The composition of the gas may show strong variations. To compare the combustion energy output (of different composition fuel gasses) the 'Wobbe Index' is used[25]. Most renewable forms of natural gas must be treated to increase the Wobbe index and to remove Hydrogen sulphide or other unwanted contaminations from the gas. The Sorpa plant produces Methane with a Wobbe index that will be high enough to assure high quality Methane (see 2.4.2) that can be used for buses.

[25] *'Long term policy on gas composition', Netherlands Government, 13 March 2012*

Options for the delivery of biogas or landfill gas:

- Transport of natural gas, biogas or landfill gas by pipeline
  The biogas or landfill gas production takes place on the outskirts of the capital area. There is a piping infrastructure directly connecting the production location to Reykjavik, as described in paragraph 2.4.2. The endpoint of the pipeline, the N1 fuelling station at Bíldshöfði, is 2km away from the Strætó depot at Hesthális.
    - It is possible for the buses to drive back and forth to the refuelling station. This can be done by night while the maintenance of the buses is done. This has implications for additional personnel.
    - The pipeline can be extended towards the Hesthális Strætó depot. A cost estimation of this extension is already made, the costs are around 110M ISK.
- Transport of natural gas, biogas or landfill gas by road
  Because of its low density, it is not easy to store natural gas or to transport it by vehicle[26]. In addition, untreated biogas has a lower caloric value than natural gas. And for landfill gas the caloric value can be even lower. Therefore, the transport of biogas or landfill gas by road will run with a poor energy efficiency, compared to transport by pipeline.

Figure 15 – CNG compressor unit, control cabinets and fuel station (Amersfoort - Haven)

Safety requirements:

- Basic safety requirements to explosive atmospheres are detailed in the European Directives 1994/09/EC (also known as 'ATEX 95' or the 'ATEX Equipment Directive') in the 1999/92/EC (also known as 'ATEX 137' or the 'ATEX Workplace Directive') and in the 2009/142/EC (European Gas Appliances Directive).
- Basic safety requirements to the Electrical Safety are detailed in the international standards EN 50110, EN 50522 and IEC 61936;

[26] *Source: https://en.wikipedia.org/wiki/Natural_gas*

Other successful applications of biogas or landfill gas can be found in the co-generation of electrical power and heat, in the heating of buildings and in local applications. Return of investment is depending on existing networks for natural gas, as these may be used for the distribution of the biogas or landfill gas.

Future applications within the transport sector are foreseen within aviation and navigation[27]. Within the transport sector, on the long term, only limited applications remain[28]:
"(…) that the increased use of natural gas in road transport is largely ineffective in reducing greenhouse gasses or air pollution. The immediate benefits are small or non-existent while the environmental costs, societal costs and costs to operators are negative for almost all vehicle categories. Expanding the use of natural gas in vehicles also runs counter to the efforts to reduce EU's gas imports and energy dependence (…) Although waste-based bio-Methane can deliver significant GHG savings, it can only be supplied for niche applications, due to the limited sustainable supply.".

4.4.3 Impact on operations

Buses using biogas or landfill gas normally have a driving range of around 500 km. However, current operation of Methane buses by Stræto shows that in Iceland conditions with the use of Methane from landfill gas, the driving range is between 200 and 250 km. This is more than a Borgarlína bus will drive every day, so there are two refuelling moments needed every day to drive the full service. One refuelling moment can be done together by night or during maintenance of the buses, the other refuelling moment has to take place during the day. The extra refuelling moment causes a need for extra vehicles, when choosing for Methane from landfill gas. The use of biogas or landfill gas will not lead to reliability issues or to additional spare requirements for the buses as needed for the operations.

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[27] *Source: 'Innovatiethema Gas en Groen Gas' (April 2015) by RVO.nl for Topsector Energie*
[28] *Report 'Natural gas in vehicles – on the road to nowhere' (March 2016), Transport and Environment, Europe's leading clean transport campaign group, as downloaded from: https://www.transportenvironment.org/sites/te/files/publications/2015_02_TE_briefing_natural_gas_road_transport_FINAL.pdf*

5 TCO Analysis

5.1 Introduction

This chapter focuses on the financial perspective in assessing the clean fuel options. To ensure a fair comparison of options, a total cost of ownership (TCO) approach is applied. This enables a comparison considering all costs over the lifespan of the project. The TCO approach includes both the initial investment costs of the assets (e.g. construction costs, purchase price or lease price) as well as the costs to maintain and operate the assets over a predefined period of time. This time period is often set to the asset's lifespan but can be extended to include lifetimes different assets.

The Fuel Selection Study compares different options of energy carriers and weighs them against each other. For this purpose, a model is used, which compares them on a yearly base, without getting into the detail level of all Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). The outcome of the calculations cannot be regarded as exact values for the CAPEX or OPEX for rolling stock, operations or infrastructure in the years to come.

The model considers the investment cost of the fleet of zero-emission vehicles, the cost of operating it and the costs of the needed infrastructure, including for instance charging facilities. All scenarios are compared to a 0-scenario, based on diesel vehicles.

5.2 TCO model and analysis explained

The total cost of ownership (TCO) analysis was done using a Dutch TCO- model, originated from the non-profit foundation CROW. This organisation operates as a knowledge institute for infrastructure, public space, traffic and transport, and work and safety. The model is developed by CROW for the specific use of comparing different clean fuels uses in public transport. For the purpose of this study, the designer of the model assisted in calibrating it.

The model calculates the total cost of ownership of deploying a fleet of zero-emission vehicles in a project or concession. Different alternatives can be compared in user-defined scenarios. This also enables a comparison of zero-emissions with a conventional scenario containing diesel vehicles.

Model inputs

To calculate the total cost of ownership of implementing a clean fuel, the model uses a set of specific inputs incorporated into the model by the developers and requires the user to provide a set of specific inputs. Inputs includes

- costs of the vehicles
- costs of necessary energy infrastructure (including transport and fuelling points)
- costs of the fuel
- cost of operating the network (including maintenance)

The values of the inputs used in the analysis are presented in paragraph 5.4.

The initial investment of an asset (e.g. vehicle) and replacement investment at the end of an asset’s lifetime can be put into the model as an upfront amount, as well as a yearly lease amount. For the analysis lease amounts were used. The life cycle of assets in certain scenarios may vary and as a result the period the TCO takes into account may just include or just exclude a replacement cost. This would skew the results. Inputting lease amounts counters this effect and provides a fair comparison between the fuel systems. The annual lease prices are calculated based on an acquisition price or construction cost, a lifetime of the asset and a real interest rate of 3%. The costs for maintenance and operations of the asset (among others fuel costs) are excluded from the lease price calculation and added separately as costs in the analysis.

Scenarios
The model is run for a set of scenarios defined by the user. Scenarios can be run for one or a combination of clean fuel implementations and all consist of a specific set of multiple input variables. Part of the analysis is a comparison of clean fuel implementation and continuing with conventional fuel use. For this a so called zero-alternative is included, sometimes referred to as the 'without-project' case. The characteristics of the scenarios included in the analysis are presented in paragraph 5.3.

Output
The TCO model provides overviews of the total costs of ownership per scenario (fuel option), expressed in cash flows projected in time. The cash flows do not include increases in pricing over time due to inflation of indexation and are therefore real cash flows.

To enable a fair comparison between scenarios and account for the time value of money, a present value calculation was added to the analysis and applied to the real cash flows from the TCO model. This summarises the total cost of ownership in one monetary amount in the present and enables fair comparison of different scenarios. For the present value calculation, a real discount rate of 3% was applied to the real cash flows.

5.3 Scenarios

Six base scenarios are run in the model using the input parameters as presented in the next paragraph. Each of these scenarios takes the 3 defined phases as a starting point and takes one single source of fuel into consideration. Scenario's with switching the propulsion system between phases are not used, due to the high initial investment costs of the electricity and the hydrogen scenario. The depreciation period of the new infrastructure would be too short to make investments viable.

From a financial perspective, new lines that are added during phase 2 and 3 are preferably using the same fuel type. If another fuel type is introduced, new investments need to be made in infrastructure and buses. However, there can be other reasons to combine multiple fuel types, such as flexibility in the future. A scenario with many options (e.g. the possibility to expand after several years or change the concept) is theoretically worth more than a scenario that limits in one direction for the next few decades. A small investment in a first phase can create a valuable opportunity in a second phase. This is discussed further in chapter 7.

The six scenarios used are:
- Diesel (zero alternative)
- Methane from landfill gas (CNG)
- Electricity (Opportunity Charging)
- Electricity (Plug-in Charging[29])
- Electricity (Plug-in with diesel heater)
- Hydrogen

For some scenarios a sensitivity analysis is made, to provide a better comparison against other fuels.

[29] *Plug-in charging only takes place at the depot. With opportunity charging the buses are charged both during the day (opportunity charging) and at the depot (plug-in charging).*

5.4 Input

All input in the TCO model is based on local conditions or key figures gathered through field knowledges. All variables are separately adjustable for future use.

5.4.1 General

€	ISK
1	149.95

Table 10 - Exchange rate used

Years	2024-2043[30]				2029-2043			2034-2043
Line	**A**	**B**	**C**	**Strætó 25%**	**D**	**F**	**Strætó 100%**	**E**
Diesel, H2	7	7	6	31	6	6	90	7
CNG	7	8	6	34	7	6	99	8
Electric (OC charging, electric heating)	8	8	7	36	7	6	103	8
Electric (electric heating)	10	10	10	41	10	9	116	11
Electric (fuel heating)	7	8	6	31	7	6	90	7

Table 11 - Amount of buses per line for each fuel type

Infrastructure is only added to the calculation as soon as the buses that need them start riding.

Residual value (%)	Diesel	CNG	Electric	H2
Infrastructure	0%	0%	0%	0%
Buses	10%	10%	0%	0%

Table 12 - Residual value for infrastructure and buses

Life cycle (years)	Diesel	CNG	Electric	H2
Infrastructure	30	30	15	15
Buses	10	10	15[31]	10[32]
Battery	-	-	7	-

Table 13 - Life cycle in years for infrastructure, buses and batteries

Borgarlína network	Strætó network
3 (l/h) / 40 (km/h) = 0,075 l/km	3 (l/h) / 20 (km/h) = 0,150 l/km

Table 14 - Diesel consumption of diesel heater

[30] Calculating with 20 years average, from the start of the phase
[31] Research finds a longer life cycle for electric vehicles than for diesel vehicles
[32] Research finds that the lifecyle of Hydrogen buses might be similar to electric vehicles, but since there is not enough data availble yet, this study uses a conservative approach on the life cycle.

5.4.2 Diesel

	Cost (€)	Lease (€ /year)	Yearly cost (€ / year)
Price	1,49 / L[33]	-	-
Infrastructure (4+4 pumps)	4 * 35.000[34]	4 * 1.734	4 * 1.500[35]
Buses (20+12+7 Diesel Euro VI bus 18m) *(consumption 0,36 l/km)*[36]	39 * (350.000 + 50.000 (ICT))[38]	39 * 48.914	39 * (6.250 + 3.600) (maintenance + refurbishment)[40] + 0,35 / km[41]
Buses (31+90 Diesel Euro VI bus 12m) *(consumption 0,28 l/km)*[37]	121 * (280.000 + 50.000 (ICT))[39]	121 * 34.240	121 * (6.250 + 3.600) (maintenance + refurbishment)[42] + 0,28 / km[43]

5.4.3 CNG

	Cost (€)	Lease (€ /month)	Yearly cost (€ / year)
Price	1,01 / kg[44]	-	-
Infrastructure (1+2 station for 50 buses)	3 * 850.000[45]	3 * 42.103	3 * 8.500[46]
Buses (21+13+8 CNG bus 18m) *(consumption 0,57 kg/km)*	42 * (380.000 + 50.000 (ICT))[47]	42 * 52.583	42 * (6.250 + 3.600) (maintenance + refurbishment)[49] + 0,40 / km[50]
Buses (34+96 CNG bus 12m) *(consumption 0,41 kg/km)*	130 * (280.000 + 50.000 (ICT))[48]	130 * 34.240	130 * (6.250 + 3.600) (maintenance + refurbishment)[51] + 0,33 / km[52]

[33] *224 ISK/L, provided by Strætó bs*
[34] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[35] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[36] *Dutch figures from CROW summarized by CROW (2015) retrieved from https://rocov-nh.nl/wp-content/uploads/2018/01/CROW-Kostenkengetallen-regionaal-OV.pdf*
[37] *Dutch figures from CROW summarized by CROW (2015) retrieved from https://rocov-nh.nl/wp-content/uploads/2018/01/CROW-Kostenkengetallen-regionaal-OV.pdf*
[38] *Dutch figures from CROW summarized by CROW (2015) retrieved from https://rocov-nh.nl/wp-content/uploads/2018/01/CROW-Kostenkengetallen-regionaal-OV.pdf*
[39] *Dutch figures from CROW summarized by CROW (2015) retrieved from https://rocov-nh.nl/wp-content/uploads/2018/01/CROW-Kostenkengetallen-regionaal-OV.pdf*
[40] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[41] *Dutch figures from CROW unpublished.*
[42] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[43] *Dutch figures from CROW unpublished*
[44] *152 ISK/kg provided by Strætó bs*
[45] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[46] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[47] *10% more expensive than diesel by Dutch expert*
[48] *10% more expensive than diesel by Dutch expert*
[49] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[50] *EUR 0.05/km more expensive than Diesel by expert*
[51] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[52] *EUR 0.05/km more expensive than Diesel by expert*

5.4.4 Electric OC

	Cost (€)	Lease (€ /month)	Yearly cost (€ /year)
Price	0,11 / kWh[53]	-	-
Infrastructure (59+116+8 slow charge	183 * 30.000[55]	183 * 2.440	183 * 1.500[62]
Electric compact station bus depot	300.000[56]	24.398	15.000[63]
26+33+4 fast charge	63 * 300.000[57]	63 * 24.398	63 * 15.000[64]
5 Electric compact stations	5 * (150.000[58] + 10.000 (200/m2[59] * 50m2 (land)))	5 * 13.012	5 * 7.500[65]
Availability high voltage connection[54]	86.000 (2 MVA depot)[60] 5 *483.000 (5 MVA OC station)[61]	7.431 5 * 43.317	-
Buses (23+13+8 Electric Plug-in bus / OC 18m) *(consumption 2,30 kWh/km[66])*	44 * (400.000 + 50.000 (ICT))[67]	44 * 36.597	44 * (6.250 + 3.600) (maintenance + refurbishment)[70] + 0,32 / km[71]
Buses (36+103 Electric Plug-in bus / OC 12m) *(consumption 1,20 kWh/km)*	139 * (250.000 + 50.000 (ICT))[68]	139 * 24.398	139 * (6.250 + 3.600) (maintenance + refurbishment)[72] + 0,25 / km[73]
Battery 350 kWh (€200/kWh)	183 * 70.000[69]	183 * 10.908	-

[53] *16 ISK/kWh provided by Strætó bs*
[54] *Infrastructure is only built when it is required.*
[55] *Price based on the fast charging infrastructure used in the Netherlands (https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a). Due to the shipping costs and the size of the public transport system, prices will more likely turn out to be higher than lower.*
[56] *Assumption based on Dutch figures from CROW unpublished, A breakdown of all object types needed for an opportunity charging station is given in paragraph 4.2.4. All object types go along with costs to design, build and operate the equipment.*
[57] *Price based on recent projects in Amsterdam, Netherlands (https://api1.ibabs.eu/publicdownload.aspx?site=vervoerregio&id=100090614), recent calculations for an opportunity charging system in Flevoland, Netherlands (300.000-400.000 euro) and the complexity of the system in Reykjavík.*
[58] *Dutch figures from CROW unpublished*
[59] *30.000 ISK/m2 for residential areas from VSO Consulting*
[60] *Icelandic figures obtained from Veitur (2020)*
[61] *Icelandic figures obtained from Veitur (2020)*
[62] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[63] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[64] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[65] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[66] *Based on average consumption*
[67] *Dutch figures from CROW unpublished*
[68] *Dutch figures from CROW unpublished*
[69] *https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/ and https://www.mdpi.com/2071-1050/12/10/3977/pdf and https://www.globenewswire.com/news-release/2019/06/19/1870974/0/en/Global-Commercial-Vehicle-Electrification-Study-2019-The-Cost-of-Batteries-is-Expected-to-Fall-from-an-Industry-Average-of-225-kWh-in-2018-to-80-kWh-in-2035.html*
[70] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[71] *10% more than mentioned in Dutch figures from CROW unpublished because of heavy battery*
[72] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[73] *10% more than mentioned in Dutch figures from CROW unpublished because of heavy battery*

5.4.5 Electric Plugin

	Cost (€)	Lease (€ /month)	Yearly cost (€ /year)
Price	0,11 / kWh[74]	-	-
Infrastructure (71+135+11 slow charge)	217 * 30.000[75]	217 * 2.440	217 * 1.500[78]
Electric compact station bus depot	300.000[76]	24.398	15.000[79]
Availability high voltage connection	86.000 (2 MVA depot)[77]	7.431	-
Buses (30+19+11 Electric Plug-in bus 18m) *(consumption 2,30 kWh/km)*	60 * (350.000 + 50.000 (ICT))[80]	60 * 32.531	60 * (6.250 + 3.600) (maintenance + refurbishment)[83] + 0,29 / km[84]
Buses (41+116 Electric Plug-in bus 12m) *(consumption 1,20 kWh/km)*	157 * (200.000 + 50.000 (ICT))[81]	157 * 20.332	157 * (6.250 + 3.600) (maintenance + refurbishment)[85] + 0,22 / km[86]
Battery 500 kWh (€200/kWh)	217 * 100.000[82]	217 * 15.583	-

[74] *16 ISK/kWh provided by Stræto bs*
[75] *Price based on the fast charging infrastructure used in the Netherlands (https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a). Due to the shipping costs and the size of the public transport system, prices will more likely turn out to be higher than lower.*
[76] *Assumption based on Dutch figures from CROW unpublished*
[77] *Icelandic figures obtained from Veitur (2020)*
[78] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[79] *5% of infrastructure cost adapted from Dutch figures from CROW unpublished*
[80] *Dutch figures from CROW unpublished*
[81] *Dutch figures from CROW unpublished*
[82] *https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/ and https://www.mdpi.com/2071-1050/12/10/3977/pdf and https://www.globenewswire.com/news-release/2019/06/19/1870974/0/en/Global-Commercial-Vehicle-Electrification-Study-2019-The-Cost-of-Batteries-is-Expected-to-Fall-from-an-Industry-Average-of-225-kWh-in-2018-to-80-kWh-in-2035.html*
[83] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[84] *Dutch figures from CROW unpublished*
[85] *Dutch figures from Vervoerregio Amsterdam summarized by Werner Advies (2016) retrieved from https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a*
[86] *Dutch figures from CROW unpublished*

5.4.6 Electric Plugin Diesel Heated

	Cost (€)	Lease (€ /month)	Yearly cost (€ /year)
Price	0,11 / kWh	-	-
Infrastructure (52+103+7 slow charge)	162 * 30.000[87]	162 * 2.440	162 * 1.500
Electric compact station bus depot	300.000[88]	24.398	15.000
Availability high voltage connection	86.000 (2 MVA depot)[89]	7.431	-
Buses (21+13+7 Electric Plug-in bus (DH) 18m) *(consumption 1,5 kWh/km)*	41 * (350.000 + 50.000 (ICT) + 10.000 (Diesel Heater))	41 * 33.344	41 * (6.250 + 3.600) (maintenance + refurbishment) + 0,29 / km
Buses (31+90 Electric Plug-in bus (DH) 12m) *(consumption 0,8 kWh/km)*	121 * (200.000 + 50.000 (ICT) + 10.000 (Diesel Heater))	121 * 21.145	121 * (6.250 + 3.600) (maintenance + refurbishment) + 0,22 / km
Battery 500 kWh (€200/kWh)	162 * 70.000[90]	162 * 15.583	-
Diesel Heater Consumption	1,49 / L		2.796.000 km/y * 0,075 l/km * €1,49/l (Borgarlína 2024-2028) 4.769.000 km/y * 0,075 l/km * €1,49/l (Borgarlína 2029-2033) 5.952.000 km/y * 0,075 l/km * €1,49/l (Borgarlína 2034-2044 2.525.415 km/y * 0,15 l/km * €1,49/l (Strætó 2024-2028) 9.132.120 km/y * 0,15 l/km * €1,49/l (Strætó 2029-2033) 9.132.120 km/y * 0,15 l/km * €1,49/l (Strætó 2034-2044

[87] *Price based on the fast charging infrastructure used in the Netherlands (https://vervoerregio.nl/document/ae0cfdca-6039-4852-b86d-d57b48c5474a). Due to the shipping costs and the size of the public transport system, prices will more likely turn out to be higher than lower.*
[88] *Assumption based on Dutch figures from CROW unpublished*
[89] *Icelandic figures obtained from Veitur (2020)*
[90] *https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/ and https://www.mdpi.com/2071-1050/12/10/3977/pdf and https://www.globenewswire.com/news-release/2019/06/19/1870974/0/en/Global-Commercial-Vehicle-Electrification-Study-2019-The-Cost-of-Batteries-is-Expected-to-Fall-from-an-Industry-Average-of-225-kWh-in-2018-to-80-kWh-in-2035.html*

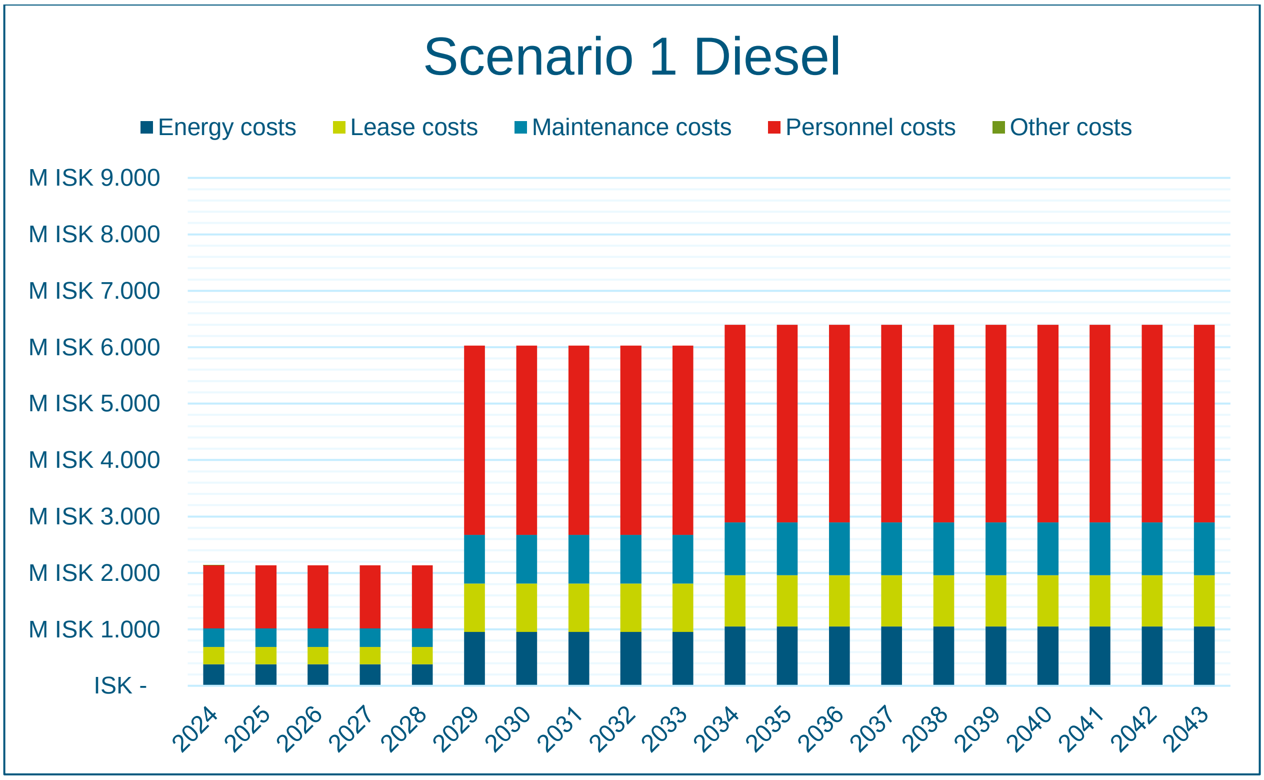
5.4.7 H2

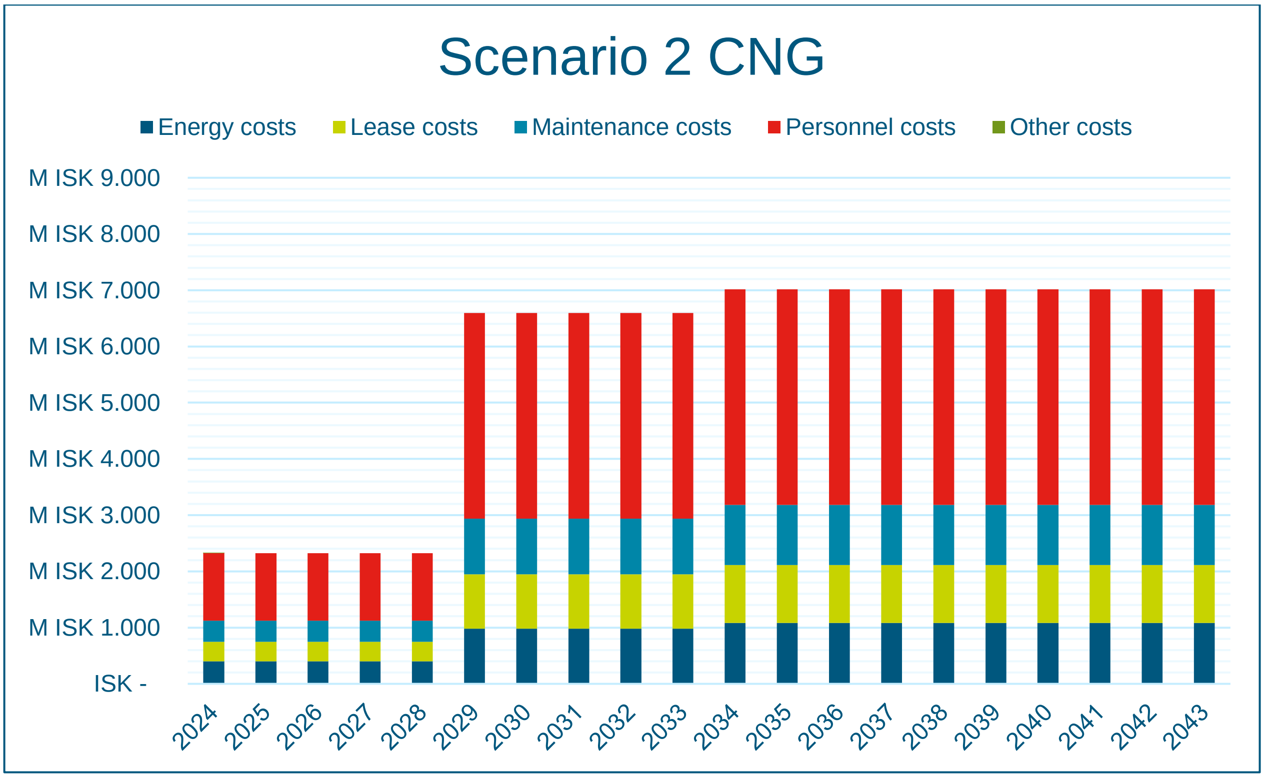
	Cost (€)	Lease (€ /month)	Yearly cost (€ /year)
Price **(supply and transport combined)**	4,39 / kg[91]	-	-
Infrastructure (1+2 station for 50 buses)	3 * 6.300.000	3 * 512.359	3 * 315.000
Buses (20+12+7 H2 bus 18m) *(consumption 0,14 kg/km)*	39 * (700. 000 + 50.000 (ICT))	39 * 60.995	43 * (6.250 + 3.600) (maintenance + refurbishment) + 0,35 / km
Buses (31+90 H2 bus12m) *(consumption 0,10 kg/km)*	121 * (650. 000[92] + 50.000 (ICT))	121 * 52.862	121 * (6.250 + 3.600) (maintenance + refurbishment) + 0,28 / km

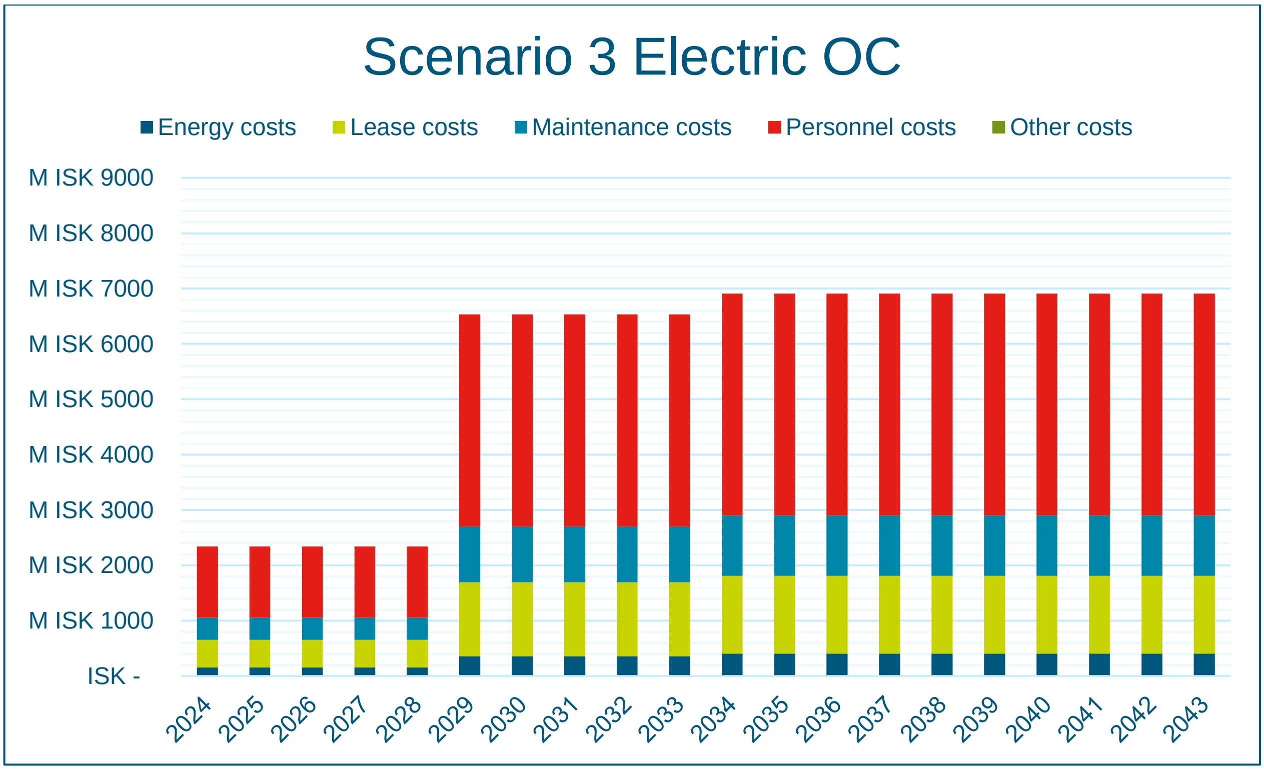
[91] *Hydrogen price (supply) is provided in dollars and converted at rate 1.077 in march 2020 for the purpose of this study..The raw price of hydrogen is provided and assured by Landsvirkjun. For the transport component, Clara Energy is consulted. The provided calculation is used conservatively, including volume and distance of the actual transport.*
[92] *Bus price based on market consultation performed during the Study. The price is supported by the ambition of the H2Bus consortium, expecting the price to drop to 500.000 euro before 2024 for 12-meter buses (www.h2bus.eu). Hydrogen Europe predicts the prices of hydrogen buses being in range of diesel vehicles around 2030 (https://www.hydrogeneurope.eu/hydrogen-buses).*

5.5 Outcome base scenarios

For each scenario, the yearly cost over time is calculated, based in the input described in paragraph 5.4. All scenarios are described in terms of total costs, broken down in energy costs, lease costs and maintenance (operational) costs.






Scenario 3 Electric OC
Energy costs
Lease costs
Maintenance costs
Personnel costs
Other costs
M ISK 9000
M ISK 8000
M ISK 7000
M ISK 6000
M ISK 5000
M ISK 4000
M ISK 3000
M ISK 2000
M ISK 1000
ISK -
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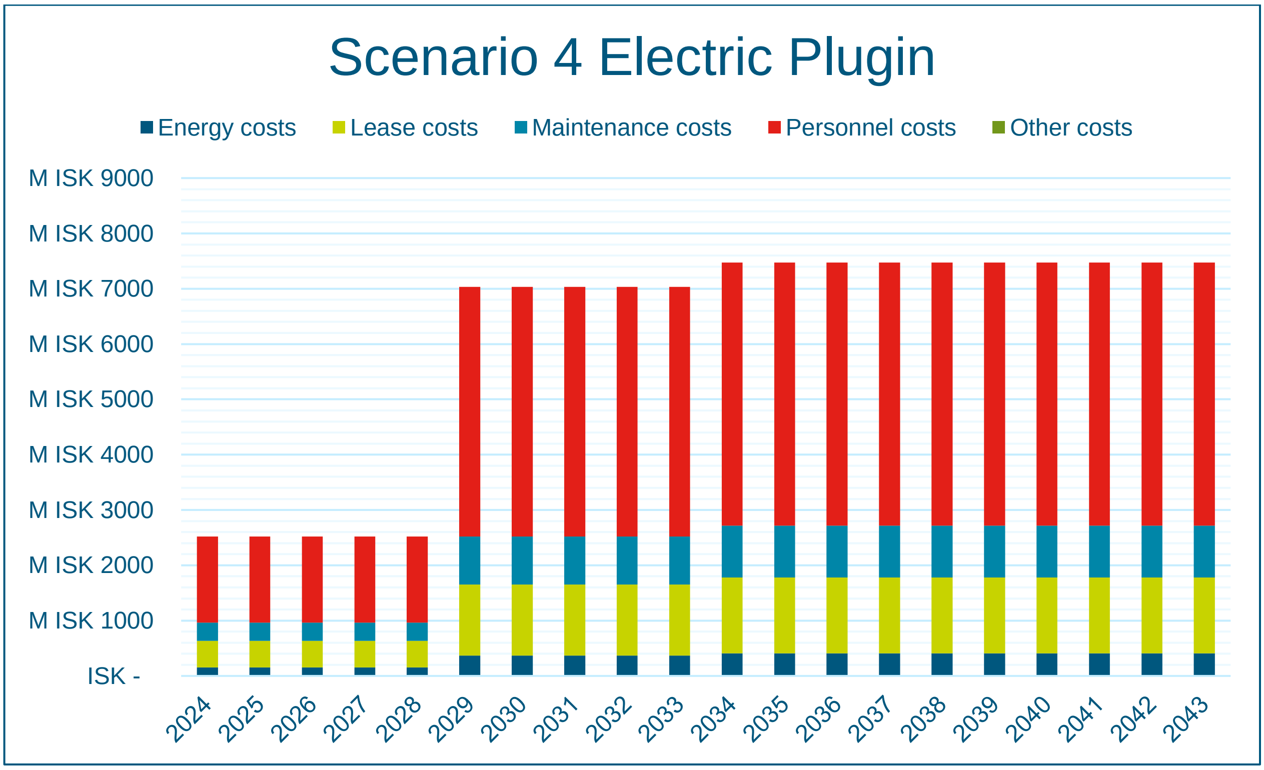
Scenario 4 Electric Plugin
Energy costs
Lease costs
Maintenance costs
Personnel costs
Other costs
M ISK 9000
M ISK 8000
M ISK 7000
M ISK 6000
M ISK 5000
M ISK 4000
M ISK 3000
M ISK 2000
M ISK 1000
ISK -
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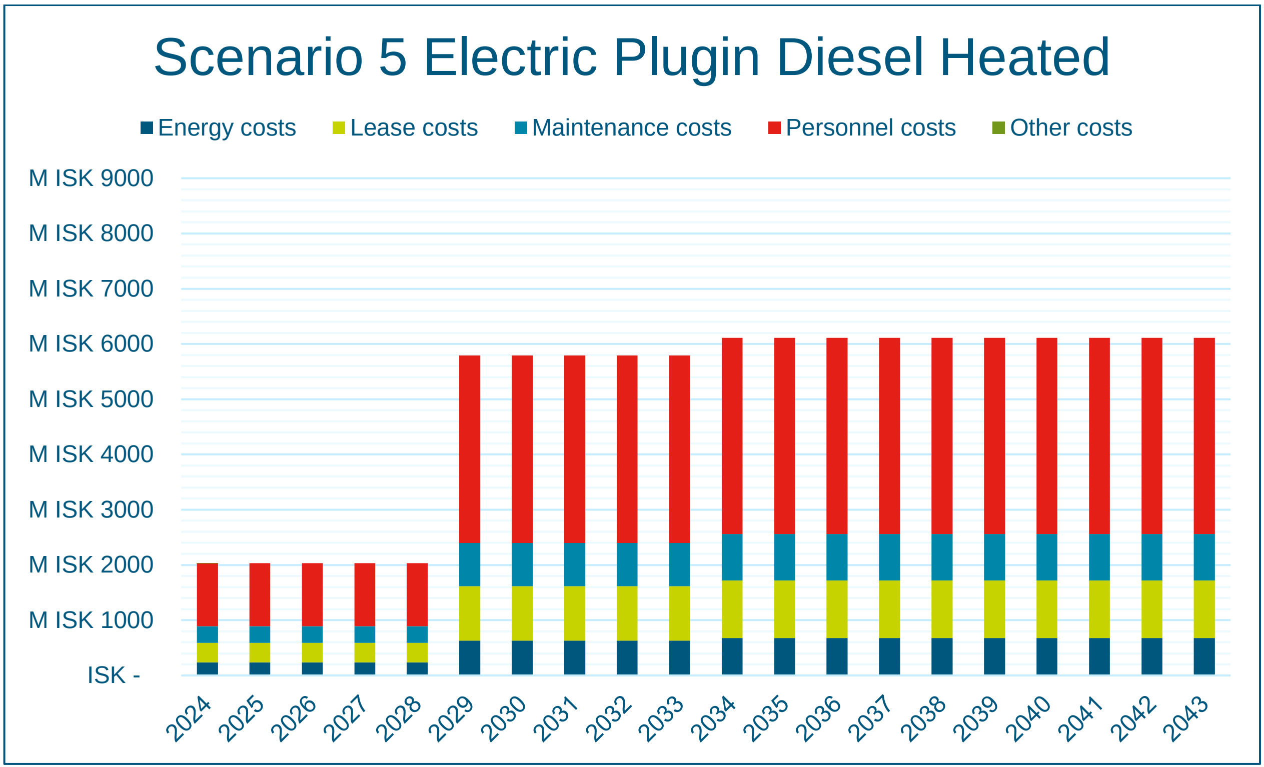
Scenario 5 Electric Plugin Diesel Heated
Energy costs
Lease costs
Maintenance costs
Personnel costs
Other costs
M ISK 9000
M ISK 8000
M ISK 7000
M ISK 6000
M ISK 5000
M ISK 4000
M ISK 3000
M ISK 2000
M ISK 1000
ISK -
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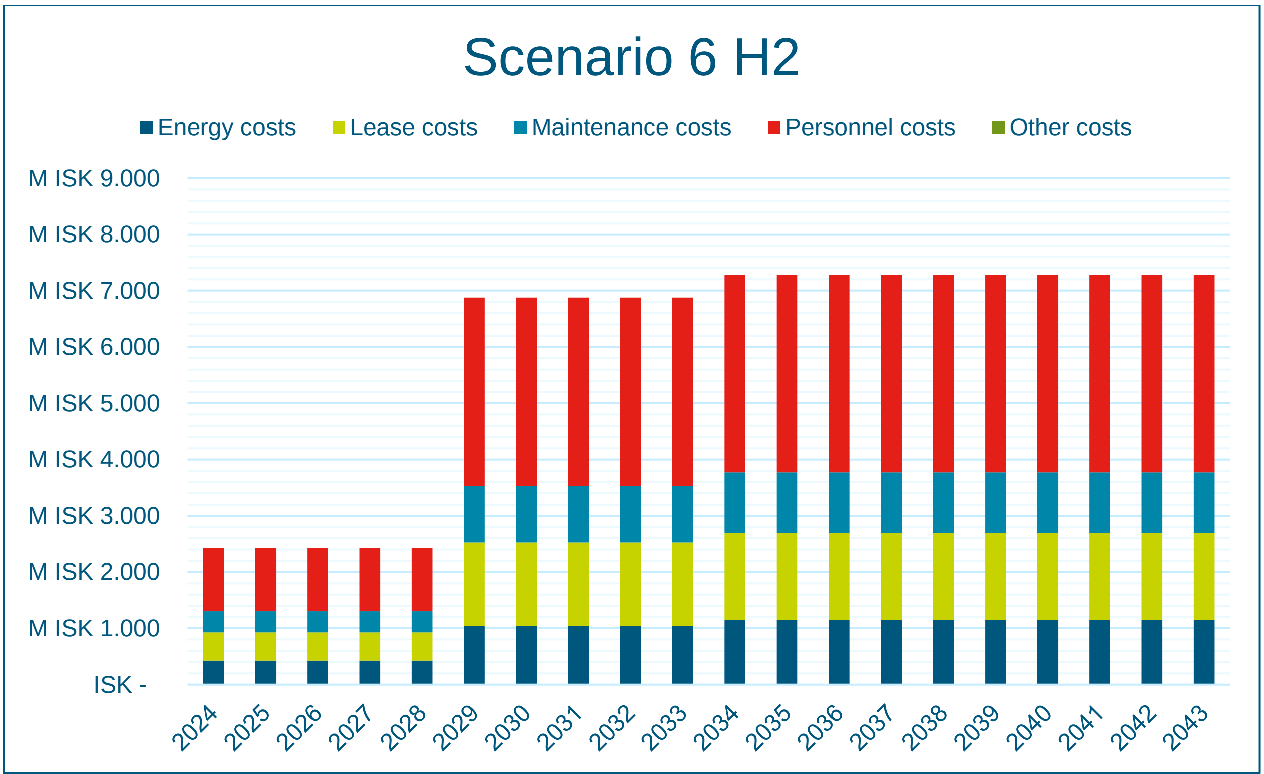
Scenario 6 H2
Energy costs
Lease costs
Maintenance costs
Personnel costs
Other costs
M ISK 9.000
M ISK 8.000
M ISK 7.000
M ISK 6.000
M ISK 5.000
M ISK 4.000
M ISK 3.000
M ISK 2.000
M ISK 1.000
ISK -
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The figures clearly show that the personnel costs are a big part of the TCO, and that the extra operational costs of refuelling and recharging moments are showing in the scenarios. The lease costs contribute the most to the TCO of Hydrogen and the electrical scenarios. In the Diesel and CNG scenarios the energy, lease and maintenance costs are more alike. In the electrical scenarios a fourth cost type can be seen; other costs. This contains the costs associated with the availability of a high voltage connection.

The zero alternative (diesel) scores the highest in terms of costs, followed by CNG and Hydrogen. Electricity (in both scenarios) is the most expensive alternative, mostly because of the investments needed in electrical infrastructure. Since lease prices are used for all scenario's, the replacement times and costs of vehicles and batteries are distributed evenly over the years.

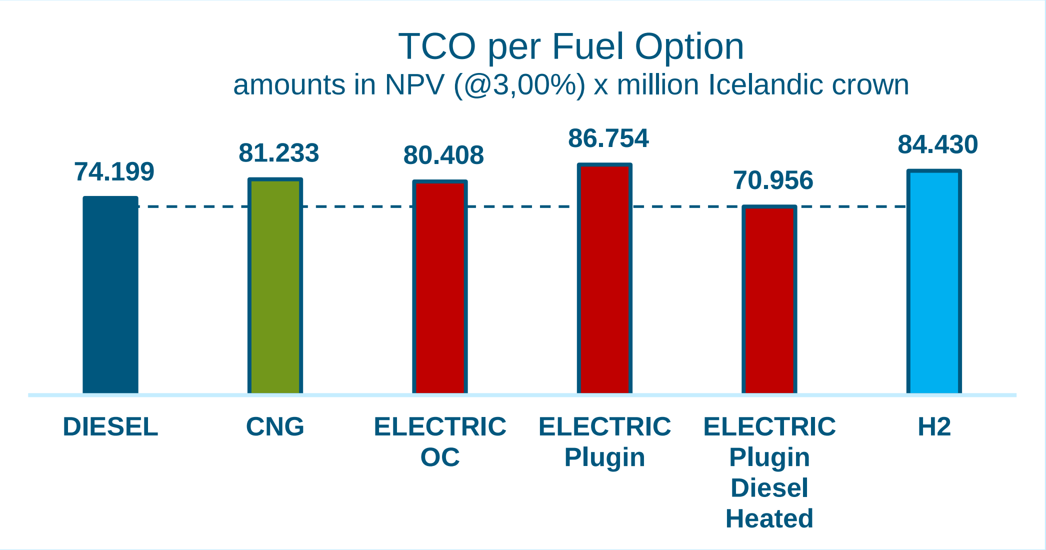
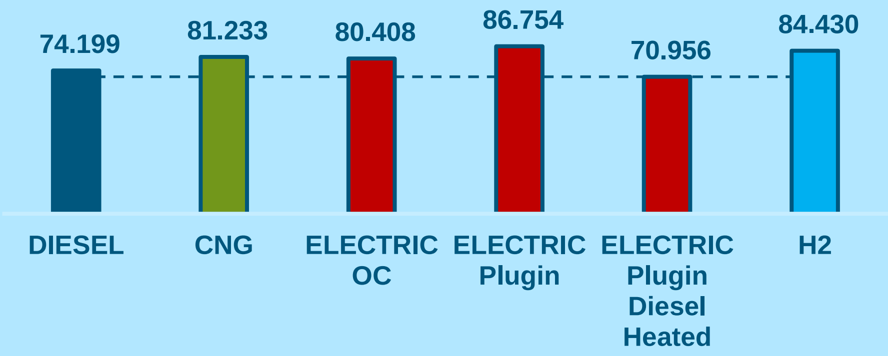


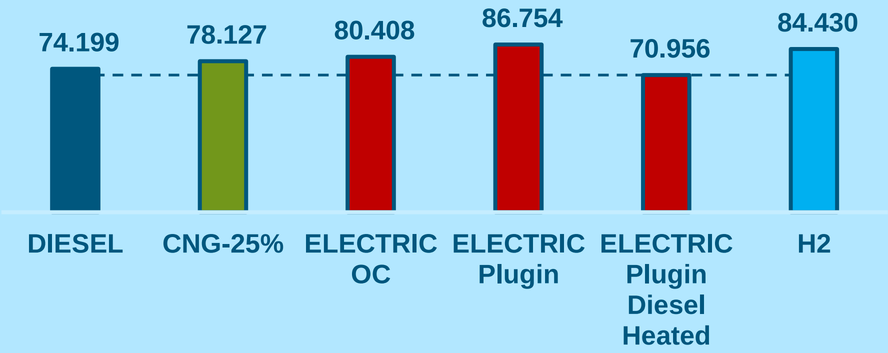
Figure 16 - TCO per scenario (x million ISK, excl. VAT in PV @3%)

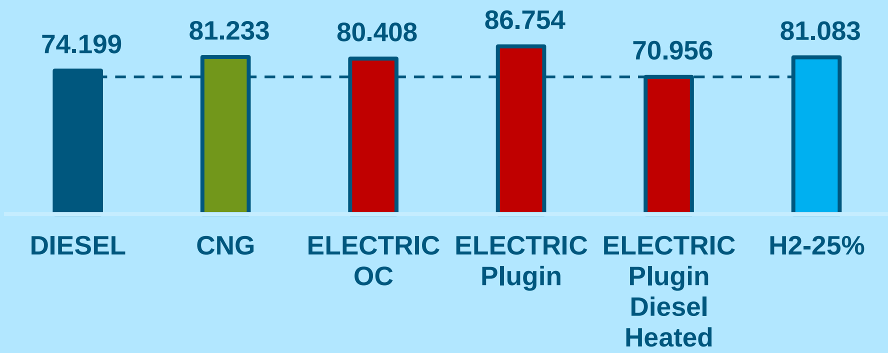
5.6 Sensitivity analysis

To assess the robustness of the end results and subsequent conclusions, a sensitivity analysis was performed. The table below presents an overview of the effects of changes in key variables on the end results. Since prices on both CNG and Hydrogen will be affected using the fuel in the public transport network, the price might be lowered to make the use more attractive. This is a logical scenario, considering the suppliers are directly or indirectly stakeholders in the Borgarlína project. Since the electricity price is very low compared to the other fuel types, there is no sensitivity analysis conducted on a lower electricity price. The main cost in the electrical scenario is the cost for the infrastructure.

<table>
<tr><th>Change in inputs</th><th>Results</th></tr>
<tr><td>Base Case

No changes</td><td>
</td></tr>
<tr><td>Lower CNG price

The CNG price is reduced by 25% to €0,76/kg (instead of €1,01).</td><td>
</td></tr>
<tr><td>Lower H2 price

The H2 price is reduced by 25% to €3,29 (instead of €4,39).</td><td>
</td></tr>
</table>

The sensitivity analysis shows that the prices of Hydrogen and CNG matter. If the Hydrogen price is lowered, the TCO is competitive with CNG.

6 Impact on environment

This chapter describes the emissions of the different fuels in a general way based on key figures and experience in the Dutch situation. We used Dutch emission factors and expertise. Therefore, this must be considered as a quick scan, a first estimation, instead of a multi criteria analysis. The actual emissions and impact of other environmental issues (e.g. vibrations) require accurate input (air-inlet temperatures, surface and building reflection characteristics) and can only be determined by more detailed calculations and measurements.

The impact analysis focusses on CO_2 (Climate), PM_{10} and NO_x (local air quality). In addition, noise, weight and vibrations are investigated.

Different situations, different emissions
The emissions are depending on mainly three factors in the following order:

4. The type of fuel
5. The type of bus
6. The type of lines

Type of bus:
For the purpose of the study, there are two types of buses considered: 18 meter buses for the Borgarlína lines and 12 meter buses for the Strætó lines. The used bus types are examples of current technology.

	BEV (electric)	FCEV (Hydrogen)	Biogas
12m bus	• Yutong E12 • Ebusco model 2.2 • VDL Citea SLF 120	• Toyota Caetano H2. Gold • Van Hool Hydrogen A330	• Mercedes-Benz Citaro NGT • Iveco CNG (Urbanway 12m)
18m bus	• Ebusco model 2.2 • VDL Citea SLE 180	• Van Hool Hydrogen Exqui.City 18 FC	• Scania Citywide LE • Iveco CNG Urbanway 18m

Table 15 - Considered vehicles

There is a distinction to make between different "lines", which is:

1. Within the city (W)
2. Outside the city (O)

All emission numbers include the stopping and starting due to traffic lights. The risk for public health requires a calculation including specific lines, atmospheric conditions and locations where people live. This is not yet part of the numbers and requires an extensive research to draw any conclusions on this matter.

6.1 Emission of greenhouse gasses

CO_2 emission
When it comes to CO_2 emission (or emission in general), there is a difference between the production phase and the usage phase which is named Well to Tank (WTT) and Tank to Wheel (TTW). These two together make the total emission (Well to Wheel). In Table 16 the emission factors are presented for different fuels. The emission factors are calculated based on the Dutch energy mix for grey (coal, oil and gas) and green energy (solar and wind).

The following observations can be made when we take a closer look at the data:

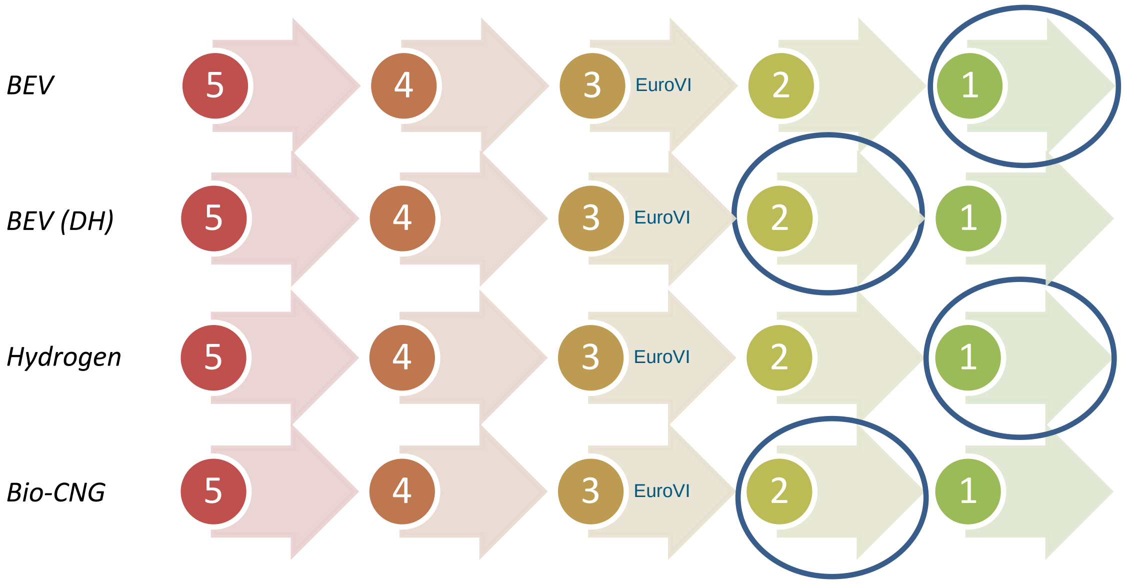
- The zero-emission options of electric and Hydrogen buses only have WTT emissions[93]. This is an additional benefit for air quality in urban areas, as electric drives do not emit harmful substances such as particle matter.
- Electric buses with diesel heaters have on average 1/3 of the emission of diesel buses. The yearly consumption of a 12m bus is 0,15 l/km, the yearly consumption of a 18m bus is 0,075 l/km. The difference is explained by the higher average speed of the 18m buses, since they are mainly used for the BRT routes.
- Emissions for biodiesel (B100) are 74% lower than those from conventional diesel[94].
- 'Grey Hydrogen' has a (very) high WTT CO_2 emission value, as 'grey Hydrogen' is produced from natural gas using energy intensive production processes (steam reforming).
- 'Green Hydrogen' has a very low WTT CO_2 emission value, as 'green Hydrogen' is produced using renewable energy for electrolysis of water.
- The given CO2 emission of 'grey' and 'green' electricity are based on the Dutch energy mixes for grey energy (coal, oil and gas) and green energy (solar and wind). For Iceland the emission factors of both grey and green energy are potentially lower due to the wide availability of hydropower and geothermal energy and thus less (environmental) costs of renewable energy production.
- The bio-CNG option counts higher emissions, but the values differ between the sources of information. Therefore, we have added several values in the table below. The emission per kilogram is used for comparison.

Fuel	Unit	Kg CO2/amount (WTW) total[95]	Kg CO2/amount (TTW) usage	Kg CO2/amount (WTT) production	Reference
Diesel (EUR)	Liter	3.200	2.580	0.620	Website CO2-e.
Diesel (EUR)	Liter (heating)	0.267			Website CO2-e.
Diesel (EUR)	Km	0,36[96]			US Energy Agency /Mannvit
Diesel (EUR)	Km (heating)	0,03			US Energy Agency /Mannvit
Hydrogen grey	Kg	12.00[97]	0.000	12.00	Website CO2-e.
Hydrogen green	Kg	0.0912	0.000	0.0912	Lansvirkjun[98]
Hydrogen green	km	0.013			
Bio-CNG	Kg	1.039	0.045	0.994	Website CO2-e.
Bio-CNG	Km	0.150 – 0.200[99]	0.120 – 0.145 -car	0.030 – 0.055 -car	Groengas NL
Electricity grey	kWh	0.556	0	0.080	Website CO2-e.
Electricity green	kWh	0.0016	0	0.0016	Landsvirkjun[100]
Electricity green	km	0.0019-0.0037			

Table 16 - Emission factors

[93] *In addition to the use of fuels small emissions come from tyres and brakes of the bus*
[94] *https://afdc.energy.gov/vehicles/diesels_emissions.html*
[95] *Source: www.co2emissiefactoren.nl/*
[96] *Source: Earlier presentation of Mannvit, data based on US Energy Agency*
[97] *Hydrogen: The energy content of Hydrogen is 120 MJ/kg and 90,66gram/liter. And to determine the CO2:*
- *Grey: 100 gram CO2/MJ.*
- *Green: 6,31 gram CO2/MJ*

[98] *https://annualreport2019.landsvirkjun.com/media/climate-accounts-20191.pdf*
[99] *Source: www.groengas.nl*
[100] *The production of green electricity demands CO2 in the building process of the installations. Average WTT emissions can be found in https://annualreport2019.landsvirkjun.com/media/climate-accounts-20191.pdf*



6.2 Air pollution and air quality

Besides CO_2, the emissions caused by burning fuels are mainly NO_x and PM_{10}[101]. The emission of PM_{10} is also caused by wear of tires, brakes and road surface. The quality of the roads and the materials used (asphalt or concrete) affects the PM_{10}-emissions. Another important emission is "Elementary Carbon" (EC), which contains the soot particles, this Elementary Carbon causes higher risks for public health than PM_{10}. When it comes to this emission, there is a big difference between older and newer diesel buses. In this study, we only refer to the newest, cleanest standard, which is Euro6.

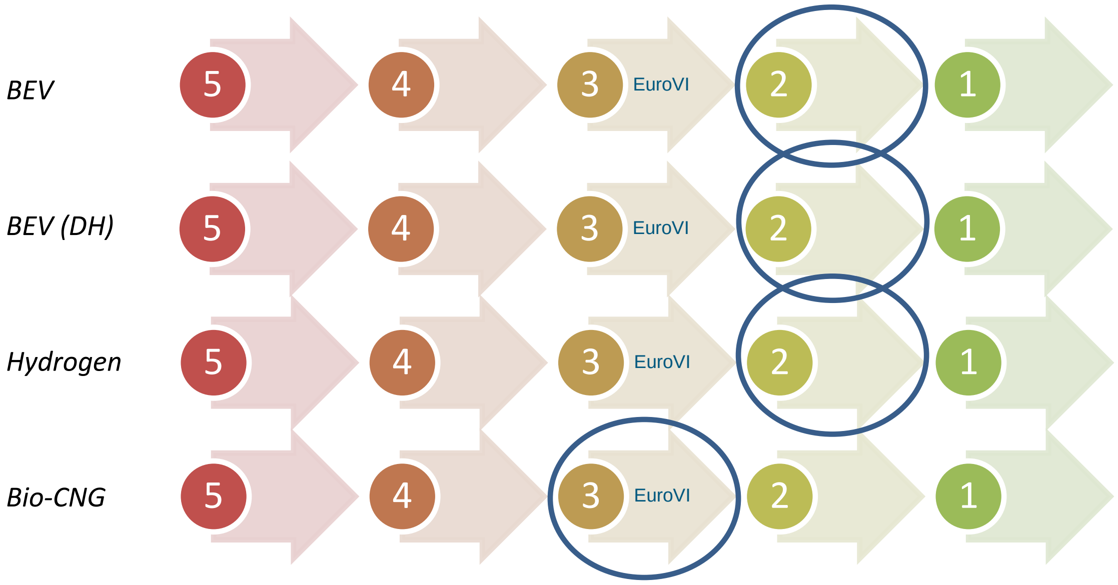
Fuel	Type of line	PM (exhaust) (gram/km)[102]	PMS (wear on tires, brakes and road surface)[103]	PM_{10} (in total) (gram/km)
Diesel	Within the city	0.015	0.092	0.107
	Outside the city	0.009	0.051	0.06
Hydrogen	Within the city	0	0.068	0.068
	Outside the city	0	0.043	0.043
Electricity	Within the city	0	0.068	0.068
	Outside the city	0	0.043	0.043
Electricity	Within the city	0.001	0.068	0.069
(diesel heater)	Outside the city	0.001	0.043	0.044
Bio-CNG	Within the city	0.015	0.092	0.107
	Outside the city	0.009	0.051	0.06

Table 17 - PM_{10} emission

The following figure illustrates the 'score' of the alternative fuels, compared with diesel. PM_{10}-emissionfactors are significantly lower due to the lower amount of pollutant particles in gasses. Because a

[101] *EPA: PM stands for particulate matter (also called particle pollution): the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope.*
Nitrogen Oxides form when fuel is burned at high temperatures. NO_x is mainly composed of nitric oxide (NO), lesser quantities of NO_2. NO_2 is of primary concern as it affects human health at elevated levels, reacts to form acids, and is a precursor for the formation of other pollutants such as particulate matter, ozone (O3) and other oxidants. Although NO alone is not a primary concern for health, it is oxidised in the atmosphere forming NO_2 mainly in the presence of O_3.
[102] *Source: TNO and Emissie registratie*
[103] *Source: TNO and Emissie registratie*

significant part of the PM_{10}-emissions are caused by wear of brakes, tires and road surface, there's limited benefits of Hydrogen and electric buses on this substance.



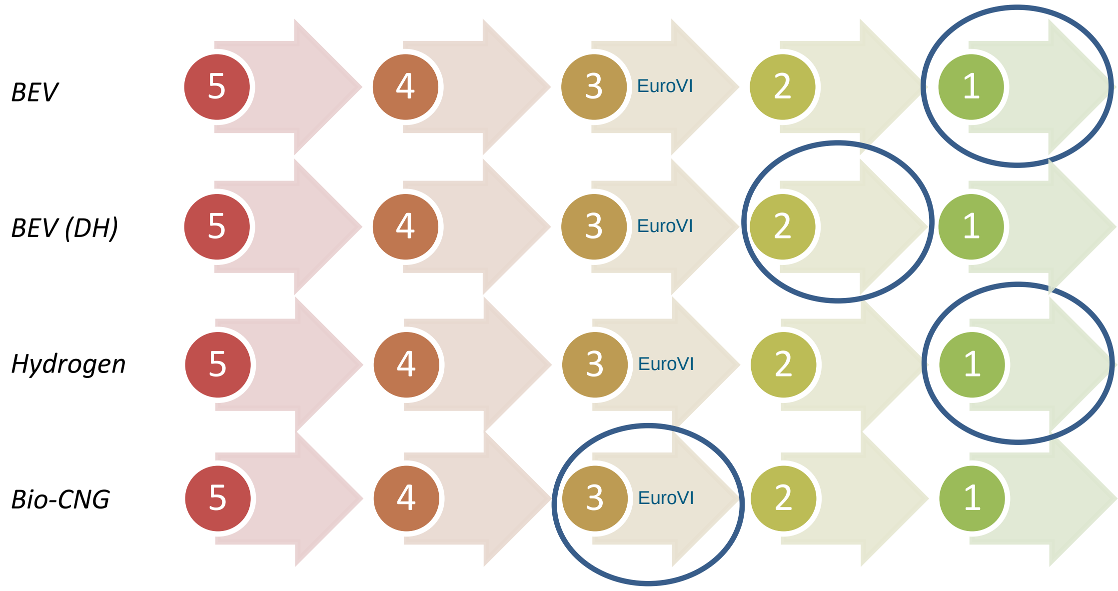
In the case of NO_x, the differences due to congestion can become quite significant when it comes to diesel. Therefore, this variation is included in Table 18. The zero emission options of electric and Hydrogen buses only have WTT emissions.

Fuel	Type of line	NO_x[104] (average) (gram/km)	NO_x (free of congestion) (gram/km)	NO_x (congestion high) (gram/km)
Diesel	Within the city	0.695 - 1	0.493	1.112
	Outside the city	0.419 – 0.61		
Hydrogen	Within the city	0	0	0
	Outside the city	0	0	0
Electricity	Within the city	0	0	0
	Outside the city	0	0	0
Electricity	Within the city	0.06 – 0.08	0.04	0.09
(diesel heater)	Outside the city	0.03 – 0.05		
Bio-CNG	Within the city	0.6 – 0.69		
	Outside the city	0.42 – 0.6		

Table 18 - Variation in emission of NO_x

The following figure illustrates the 'score' of the alternative fuels, compared with diesel. Electricity and Hydrogen are zero-emission. Hydrogen can contain a small amount of NO_x, but in all relevant databases it is noted as 0. The figures show that the NO_x-emissions of the current EURO VI diesel buses are about equal to the bio-CNG versions.

[104] *Source: TNO and Emissie registratie*

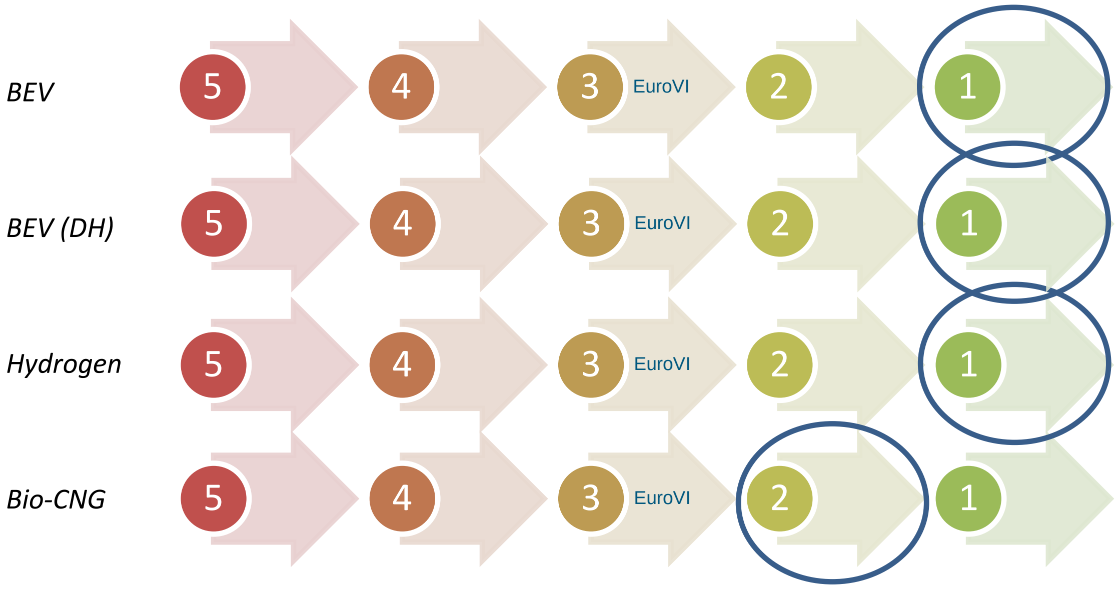


6.3 Noise

Noise has to do with many factors. The effect of noise is highly related to:

- The type of engine (related to the type of fuel)
- The type of tires
- The material of the road
- The local context (urban, suburban or more rural areas) and surroundings of the bus, and the presence of other sources of noise. It also depends on the amount of traffic and the time (day and night).
- Speed: the speed of 50 kilometres per hour is the tipping point when the air along the bus and the noise of the tires is determining the total noise, instead of the engine. Below this speed, the engine is the crucial factor.

Some information sources, including the Mannvit presentation, mention a small difference between Hydrogen and battery electric buses. By our knowledge, there is no significant difference between these two fuels when it comes to noise. Both are very quiet. The diesel heated buses are also quiet on average. Obliged by European law on traffic safety, in 2021 new electric cars are required to make a noise of at least 56 dB if they drive faster than 20 kilometres per hour. In London, the public transport company (TfL) took the initiative to add such a noise to their buses as well. When it comes to bio-CNG the noise is partly reduced by the slower combustion of the fuel.



6.4 Weight

For the differences in weight, we refer to the selection of buses mentioned before. Table 19 shows that the differences between models of the same fuel type is greater than the difference between fuel types.

	BEV (electric)	FCEV (Hydrogen)	Biogas
12m bus	• Yutong E12 **18.500 kg** • Ebusco model 2.2 **12.850kg** • VDL Citea SLF 120 **13.250 kg**	• Toyota Caetano H2. Gold **Weight unknown** • Van Hool Hydrogen A330 **14.000 kg**	• Mercedes-Benz Citaro NGT **19.500 kg** • Iveco CNG (Urbanway 12m) **12.390 kg**
18m bus	• Ebusco model 2.2 **29.000 kg** • VDL Citea SLE 180 **19.000 kg**	• Van Hool Hydrogen Exqui.City 18 FC **29.000 kg**	• Scania Citywide LE **18.800 kg** • Iveco CNG Urbanway 18m **19.000-30.000 kg**

Table 19 - Vehicle weight

6.5 Vibration

However electric engines cause less vibrations than combustion engines, vibration is most of the time not related to fuel but to other factors. Information on this is mostly gathered by the method of measuring in local situations. This cannot be done in this study and requires more research to draw any conclusions. In such a research, the following factors should be considered:

- Soil conditions
- The material and foundation of the road
- Axle pressure
- Speed
- Distance between houses and the road
- Foundation of the road

7 Conclusions and advice

The Borgarlína is the new Bus Rapid Transport (BRT) system in Reykjavík area, connecting most capital area destinations. Borgarlína wants to set a standard on using clean domestic fuel. For this purpose, three major options have been regarded:

1. Battery-powered Electric Vehicles (BEV, 3 scenario's)
2. Fuel Cell powered Electric Vehicles (FCEV, Hydrogen)
3. Internal Combustion Engines (ICE) using CNG

This report compared qualitative and quantitative aspects of all options compared to the current use of diesel-fuel and considers all three phases of the implementation of the Borgarlína network.

Based on the combination of the total cost of ownership and impact on the environment, **both Hydrogen and electricity (plug-in) are suitable and future-proof sustainable fuels for the Borgarlína network**. Compared to CNG and electricity with the use of diesel heaters, the wider impact on the environment and the future of the technology are decisive factors. The spatial impact and the lack of flexibility are the main factors not to choose the electricity scenario with opportunity charging. Between Hydrogen and electricity (plug-in), hydrogen has the advantage of the lower costs and the strong development of technology, where electricity can make use of a growth model with the use of diesel heaters to overcome range issues.

7.1 Assessment Framework

In the assessment framework, the findings of chapter 5 and 6 are summarised, to provide an overview over the various scenarios. Diesel is considered the bases scenario and therefore not part of the assessment framework. All sustainable fuels are scored against the base scenario (diesel), and if needed provided with summarised context.

Fuel	Methane	Electricity (OC)	Electricity (PI)	Electricity (DH)	Hydrogen
TCO	**0/-** 81M ISK Sensitivity Lower CNG prize (25%) **0/-** 78M ISK	**0/-** 80M ISK	**-** 87M ISK	**+** 71M ISK	**-** 84M ISK Sensitivity Lower H2 prize (25%) **0/-** 81M ISK
Lifetime GHG emissions (Kg CO_2/km WTW)	**+** 0.15-0.2	**++** 0.0019-0.0037	**++** 0.0019-0.0037	**0/+** 0.267-0.271	**++** 0.013
Local emissions PM_{10} (exhaust g/km) PM_{10} (wear g/km) PM_{10} (total g/km) NO_x (avg g/kg	**0** 0.015 0.092 0.107 0.6-0.69	**++** 0 0.068 0.068 0	**++** 0 0.068 0.068 0	**+** 0.001 0.068 0.069 0.06-0.08	**++** 0 0.068 0.068 0
Noise levels	**+**	**++**	**++**	**++**	**++**
Vibrations		To be determined			
Weight of vehicles		The differences between models of the same fuel type is greater than the difference between fuel types			

Spatial impact	**0** Most infrastructure is already available	**--** Infrastructure for opportunity charging at hubs has a big spatial impact on the area around several hubs.	**0/-** Plug-in infrastructure at the depot needed	**0/-** Plug-in infrastructure at the depot needed	**0/-** Filling station close or at the depot needed.

7.2 Total Cost of ownership

The outcome of TCO model shows the electrical plug-in scenario's to be the most expensive. Methane, electricity with opportunity charging and hydrogen don't differ much from each other. The electric scenario with plug-in buses and diesel heater turns out to be the best scenario regarding the total costs of ownership. This scenario also outperforms the diesel scenario on the long term.

Since CNG is a proven technology with a present infrastructural network, and Hydrogen is a technology in development, the costs of the Hydrogen vehicles are expected to be lowered over time. The costs of electrical vehicles are also expected to decrease some more, but not in the same extend as Hydrogen vehicles. Part of the shift towards affordable vehicles has already been made in the field of electrical vehicles.

The investment in the Hydrogen infrastructure will sustain over 15 years and will pay off in time. In the long-term perspective, this will make Hydrogen competitive with other fuels pricewise once the initial investments in the Hydrogen technology are made. The sensitivity analysis shows that a lower Hydrogen price makes the total costs of ownership comparable with the costs of CNG.

The investment in the electric plug-in infrastructure can be used for a model in which at first buses with diesel heaters are used. Over time the buses with diesel heaters can be replaced with fully electric plug-in buses to reach a sustainable solution.

7.3 Wider impact

7.3.1 Emission

The goal of the study was to determine the best sustainable fuel available. The scope of the study exceeds just the determination of costs, but also considers the wider impact of the use of each vehicle. The emissions are an important factor and will determine the future image of the Borgarlína network. CNG is considered a sustainable fuel, but scores lower than the alternatives in terms of lifetime emissions and local emissions. Electricity and Hydrogen are a more sustainable alternative regarding emissions, considering the fact that green electricity and green Hydrogen will be used. Using a diesel heater on electric buses causes local emissions (in between CNG and full electrical buses), even when using 100% biodiesel (B100).

7.3.2 Operation

The spatial impact of the energy infrastructure outside of the depot of all fuel systems is low, except for opportunity charging. The investments needed for public transport hubs are severe and make the network less flexible to operate. The implementation of an opportunity charging might cause a redevelopment of important hubs or the public transport network. The impact of both fully electric vehicles as the current

CNG vehicles on operations are severe. For plug-in charging and CNG[105], a recharging/refuelling moment has to be planned during the day. Opportunity charging relies on recharging during the operations, which leads to a longer layover time. CNG however is expected to have a better range in the future. Electric buses with diesel heaters have a sufficient driving range for the current Strætó lines. The length of the Borgarlína lines exceeds the driving range, but only a few extra 18-meter buses are needed to compensate.

Another operational aspect is the flexibility of the public transport. The demographic changes in the next 20 years will affect the demand of public transport. The system needs to be able to adjust accordingly. With a fixed amount of charging hubs, the networked is restricted in its evolving capacity when choosing for opportunity charging. Redesigning the public transport with making use of centralized hubs and combined endpoints makes operation of the public transport network more efficient and has its impact on the TCO of the different fuels.

7.4 The future of technology

7.4.1 Electricity

The biggest downside of the use of electric vehicles in the operation of a public transport network is the driving range. The driving range (except for diesel heated buses) fails against diesel and against all other sustainable alternatives, and the technology is not improving fast enough to overcome this downside during the first phases of implementation of the Borgarlína network. The driving range has both a big impact on operations and a big special impact around important hubs when choosing for opportunity charging. As shown in paragraph 4.2.3, this can cause special issues at important public transport hubs, like Hlemmur. The driving range is even more restricted by the local climate conditions. Currently Strætó overcomes this issue by using electric buses with (bio) diesel heaters instead of fully electric buses. This almost doubles the driving range in the winter season but isn't considered a full sustainable solution. Electric buses with diesel heaters be used as a temporary solution, until the range of the full electric buses is sufficient. This makes investments in charging infrastructure future proof.

7.4.2 Methane

The use of Methane from landfill gas as sustainable fuel is a proven technology. There is no big development curve expected in the future, other than the driving range being improved. To achieve this, Stræto is exchanging and comparing data and experience with CNG vehicles with public transport operators of other Nordic countries. The emission of the use of Methane will stay to be the biggest drawback and making it less of a sustainable fuel. Since the production of Methane from landfill gas is done by a government owned company, the use of Methane can also be part of a political decision. A major concern is the availability of enough Methane from landfill gas. The yearly total production of Sorpa will be around 8 MNm^3, while the total consumption off all Borgarlína lines and the Stræto network is estimated at 13 MNm^3/year.

7.4.3 Hydrogen

The development of the Hydrogen technology is very promising. The use of Hydrogen can be sustainable and safe when rolling stock, infrastructure and operations are compliant to all current EU directives. The poor energy efficiency of Hydrogen may turn out irrelevant in case an excess of sustainable energy is available from hydropower and geothermal origin. This leads to good perspectives for Hydrogen as the energy carrier in Fuel Cell powered Electric Vehicles (FCEV). Both in terms of costs and impact on the

[105] Whether CNG needs a refuelling moment is dependent on the quality of the gas and the local conditions. The current experience with CNG vehicles is that a refuelling moment is needed.

environment, Hydrogen is a logical choice. Currently the Hydrogen technology is still under development. Large scale applications may lead to project risks in terms of costs and the continuous availability of public transport vehicles.

The outcome of these considerations provides good perspectives for Hydrogen in the long term. Taking part in the current developments leads to a sustainable alternative to diesel in the years to come. Complementary use of short-range BEV buses, with use of bio diesel heaters, with long range FCEV buses provides good perspectives for the 2029 and 2034 milestones. Those complementary buses can make use of the current charging infrastructure at Hestháls and don't require big investments.