Renewable energy powertrain options for Ruter

A Report for Ruter –
Public Transport in Oslo and Akershus

Developed by Roland Berger Strategy Consultants,
in cooperation with Ruter

April 2015

Ruter#

Preface

Ruter is the administration company responsible for public transport services in Oslo and Akershus, Norway. Ruter plans, commissions and markets public transport in Oslo and Akershus. All operative service is performed by various operating companies that work by contract for Ruter and by NSB with local trains. Ruter is is owned by Oslo municipality (60 %) and Akershus County Council (40 %).

All public transport in Oslo and Akershus is to be powered using only renewable energy sources in 2020. This means an ambitious transformation of the bus and boat fleets in the region. Ruter's ambition is to quickly implement the solutions that we believe are the best in a long-term perspective.

Ruter has set up the project Fossil Free 2020 to work towards that target, and contracted Roland Berger Strategy Consultants to assist us in analyzing the technology and fuels options for the Oslo and Akershus region, as well as to develop a plan for how to reach the target.

This report is the result of Roland Bergers work on the objective of assisting Ruter in building an updated and validated knowledge base on battery electric buses and other renewable energy bus alternatives for public transport. The content of this report is the work of Roland Berger and do not necessarily reflect Ruter's views. In addition to this report a model was developed to evaluate the consequences of different technology mixes in Ruter's bus fleet, in terms of costs, environment and performance. The work was carried out between February and end of May 2015.

In June 2015 Ruter adopted a target for renewing the bus fleet towards 2025. This includes a dynamic approach to technology, specifying the need to closely follow technology and market developments. Ruter would like to see this report assisting public transport in other cities in their decisions towards low and zero-emission bus fleets. We would also hope to receive information in return, in order to keep this knowledge base as updated and relevant as possible.

Oslo, June 2015
Ruter

Executive Summary

There are increasing demands on public transport to introduce renewable solutions. Urban traffic is a concern for all large European cities since the traffic causes pollution, noise and health issues. A growing population creates needs for a large scale, efficient and environmentally friendly public transport system.

Requirements on reduced emissions create a need for new bus technologies. With the introductions of EURO I-VI requirements, significant reductions have been made with regards to local emissions (Particulate matter (PM) and Nitrogen Oxides (NOx)). However, Greenhouse gases (GHG, most critical is CO2) are not part of the EURO emission requirements. To improve local emissions even further and to reduce fuel consumption as well as GHG-emissions, increased usage of new bus technologies is needed.

In 2020, the public transport sector in Oslo and Akershus must be powered only by renewable energy. Ruter is responsible for transport services in Oslo and Akershus counties in Norway, serving 1.2 million people. In 2020, the public transport sector in Oslo and Akershus must be powered only by renewable energy. This calls for wide-ranging changes, especially to the bus fleet in the region. Ruter's aim is to introduce the most effective long-term solutions as quickly as possible.

The purpose of this report is to provide a fact-based and objective review of renewable powertrains, and implications for Ruter as part of its ambitions to only use renewable energy in 2020. The report is part of a larger project, whose aim is to develop certain scenarios for future fleet mixes using different alternative powertrains. Focus of this report is on alternative powertrains that could be considered possible for commercial operation within the timeframe of the study (2020 or shortly thereafter). Analyses of powertrain developments are focused to technical maturity, environmental impact, operational performance and cost. The report is based on a number of discussions and information provided from bus and infrastructure manufacturers, transport operators and other public transport authorities, as well as review of third-party information and reports.

A number of renewable bus technology solutions (biofuels and electric powertrain technologies) are expected to be available towards 2020. Key technologies with a renewable profile described in this report are: biofuels such as biodiesel, bioethanol or biogas, and new powertrains such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), fully battery electric vehicles (BEV), and fuel cell electric buses (FC).

Electric buses appear viable from a commercial readiness perspective in 2017-2018 onwards with 12 meter being more mature than 18 meter buses. Electric and fuel cell buses are still maturing and currently in test/pilot phases. Plug-in hybrid electric buses could be commercially available in 2017 (2 bus producers for both 12 and 18 meter parallel hybrid buses) and be a potential bridging solution before fully electric buses become available with lower operational risk. Full electric buses are most commercially available in 2017-2018 onwards with 12 meter being more mature than 18 meter buses. However, certain bus manufacturers have indicated that the 12 meter overnight bus already today is ready for serial production. However, these buses have not fully been tested in Nordic climates. Fuel cell buses could be potential commercial alternatives in 2020 but by fewer bus producers than for overnight and opportunity buses.

Electric infrastructure maturity is low in 2015 and further standardization is required while biodiesel, biogas and bioethanol infrastructure solutions have high technical maturity and are already installed in the Oslo region. Operators today in Oslo and Akershus have biodiesel, biogas and bioethanol buses, with associated infrastructure including tanks and pumping systems for biofuels. Biogas infrastructure is typically more complex, and therefore requires higher investments. Electric charging infrastructure relates to depots (overnight and opportunity charged buses) and in route, often end of route charging points (for opportunity charged buses). Standardization of infrastructure solutions is generally low (multiple solutions exist) and remains to be solved, with particular need for standardization of communication protocols between the bus and the charging unit. Certain standards emerging could potentially be closed or specific to certain manufacturer, which could be a potential challenge for Ruter creating potential lock-ins. Although charging infrastructure for electric buses represents significant investments, the costs are estimated to be smaller than the bus purchasing costs that will use the infrastructure. All electric charging converts AC in the normal power grid to DC to be used in the batteries (either in the bus or in converter in the depot or in the city charging infrastructure). DC charging (converting externally of the bus) has a number of benefits over AC charging. As to DC charging, a number of options exist, and the inverted pantograph appears to be the solution currently most mature and to date preferred by bus producers.

Environmental performance evaluation should primarily address differences in CO2 impact. When considering buses with Euro VI engines, main focus should be on well-to-wheel CO2-emissions due to small differences in PM and NOx-emissions. CO2 impact is highly dependent on bio-fuel feedstock used and evaluations should ideally be conducted on specific fuels with known origin, production and transport specifications. Second generation bio-fuels are preferred given its better environmental impact and sometimes better engine performance. Fully electric and fuel cell buses powered by wind and hydro power energy have the lowest well to wheel CO2–emissions, followed by PHEVs and HEVs. Among the biofuels, biogas from waste in Oslo region has the best CO2-impact but biodiesel and bioethanol could reach similar levels dependent on feedstock used. Fuel cell and electric buses also have the lowest noise levels.

Second generation biofuels are preferred over first generation and have high availability in the Oslo region. Biofuels are renewable transport fuels derived from organic materials. Biofuels can be of first, second or third generation, with less maturity in second and third generations. Second generation biofuels are available and should be preferred over first generation biofuels due to better CO2-footprint, better winter climate properties, less land-usage and no food versus fuel conflict – although at a price premium. The majority of first generation biofuels will not meet EU renewable targets of at least 60% CO2-reduction in 2018 compared to conventional diesel and second generation focus will increase.

Biofuel buses have a better driving range than electric buses. Differences in fuel energy density influence the energy consumption and driving range for the buses. An electric bus has a short driving range on one charge and needs to carry more weight in fuel batteries compared to other powertrain solutions. Biofuels have almost the same energy density as the equivalent fossil diesel which gives the advantage of having a good driving range. Biodiesel buses fulfill Ruter's requirements on daily range and can operate c.600 km before refueling, depending on type. The average driving range without refueling/recharging for an overnight bus is about 240 km and for an opportunity bus about 40 km. Overnight buses typically charge in full, opportunity charged buses have constraints in charging time and thereby the amount it can charge, which affects range. Plug-in hybrid buses normally can operate c.7-20 km in pure electric mode. Fuel cell buses typically have longer daily ranges than battery buses as the second zero emission alternative, depending on consumption, they can run 300-400 km on a single tankful.

Biodiesel has higher energy density than other biofuels (bioethanol and biogas) with high similarities to fossil diesel and is the most commonly used as secondary fuel in hybrids. Biodiesel also require limited infrastructure or bus adaptations. However, a combination of different powertrains using biofuels might still be needed in order to reach the renewable energy target 2020. Compared to other high quality biofuels with low CO2-impact, biogas as a fuel has high present availability in the Oslo area and the infrastructure is already in place.

Although the driving range is short without recharging for electric buses, the energy consumption per kilometer is low. The energy consumption reduction compared to biodiesel buses is about 60-70 % for electric buses and about 20-35% for hybrids. PHEVs (plugin hybrids) are between electric buses and HEVs depending on the degree of external charging.

Biofuel buses, overnight charged electric buses, and fuel cell buses have high route flexibility. Electric opportunity buses, with smaller batteries, requiring charging infrastructure along the route, have the lowest route flexibility.

Passenger capacity limitations have to be considered for fuel cell and overnight buses and to some extent opportunity buses. Biodiesel, biogas and bioethanol solutions can in general carry the same amount of passengers; variance is primarily given by different bus layouts. Passenger capacity for an overnight bus is c.85% and c.80 % for a fuel cell bus compared to an equivalent biodiesel bus. This is due to the high weight of the large battery that needs to be carried (due to low energy density of batteries) for the overnight bus and required powertrain components as well as additional fuel storage for the fuel cell bus. Today, the passenger capacity of an opportunity bus is about 95% of a biodiesel bus.

In 2015, c. 80% uptime is to be expected for plug-in hybrids, overnight, opportunity and fuel cell buses, compared to 98% for diesel buses. The main reasons for the low uptime of electric buses are immature supply chains leading to limited availability of spare parts and also issues regarding infrastructure downtime. The uptime is estimated to be equal to diesel buses in 2021-2025.

Biodiesel ICE and biodiesel hybrid solutions are expected to be the least costly renewable powertrain options also in 2025. Biogas and bioethanol as well as associated standard hybrid solutions are expected to have a limited price premium compared to biodiesel. Plug-in hybrid, battery and fuel cell electric buses have significantly enhanced bus purchasing costs which are expected to decrease significantly over the next years until 2020. If costs are adjusted for incurred downtime and reduced passenger capacity as well as more buses required in the fleet due to opportunity charging times, overnight and opportunity buses are significantly more expensive than biodiesel buses also in 2020 and beyond. Fuel cell buses are the most costly powertrain solution in terms of overall TCO, bus and infrastructure purchasing prices at the moment. For TCO calculations, environmental and social impact has not been included in the analysis.

Future developments of costs are uncertain and depend on a number of key factors:

- Purchasing costs of plug-in hybrid, electric and fuel cell buses are highly influenced by future technological and market developments as well as speed of deployment of new technologies – if the market for electric buses takes up in the next years, significant cost reductions can be expected
- Costs developments and lifetime expectancy for key components (batteries and fuel cells) highly impact initial purchasing and maintenance costs – With expected price reductions and performance increases of batteries of about 5% per year in the next 5-10 years the price premium for deployment of electric buses will diminish
- Fuel price development: Due to their low energy consumption, electric buses partly offset their higher initial investment cost by reduced fuel costs – If market prices or taxation for biofuels increase in the future, electric buses will have cost benefits
- Infrastructure lifetime expectancy: Currently, the expected lifetime of charging infrastructure for electric buses is uncertain due to its limited maturity and operational experience – If electric charging infrastructure can be used during the same timeframe as conventional infrastructure (~20 years), this will have a positive impact on their depreciation costs

From a CO2 well-to-wheel emission standpoint, fully electric (both overnight and opportunity), PHEVs, fuel cells, and biogas EURO VI powertrains are more or less equivalent and all very good options. Battery production has a high CO2 footprint impact that should be considered in technology assessments. Replacing the current fleet with modern EURO VI biofuel buses will also have a dramatic effect on local emissions, albeit not to zero levels. It is important to keep in mind that a broad, immediate modernization of the bus fleet to the latest biofuel standard will have a bigger total environmental effect than a gradual introduction of a few electric buses. The choice of technology should therefore weigh a number of factors including economical costs, social benefits and environmental benefits. In addition, broader life-cycle assessments may be needed (of the bus and infrastructure required).

Ruter's appetite on a number of dimensions will be important when making the powertrain choice:
- Level of ambition in the definition of "renewable"
- Willingness to pay a premium for environmental gains
- Willingness to accept risks that may impact customers (potential increase in level of service disruptions from new technologies)
- Ruter's and potential operators' ability to deal with technological changes (organization, learning etc.)

In conclusion in 2020, a number of renewable powertrain options may be commercially ready. Infrastructure maturity differs somewhat, but appears to have improved significantly compared to 2015, as can be seen in figure below. In terms of total cost of ownership (TCO), biogas, PHEV and electric buses (overnight, opportunity and fuel cell buses) will generate a total cost increase, however also improved environmental performance. Regarding total cost of ownership between different technologies, it is expected that the price premiums compared to biodiesel will diminish over time.

	Bus technology maturity level 2015	Commercial ready in 2020	Infrastructure maturity 2020	Fuel/energy availability in 2020	Reduced local emissions vs. Euro V diesel	Reduced WTW CO_2 emissions towards conventional diesel	Energy consumption	TCO Index 2020
Biodiesel	●	✓	●	✓	◕	◕	High	98-102
Bioethanol	◕	✓	●	(✓)[1]	◕	◕	High	103-108
Biogas	●	✓	●	(✓)[1]	◕	◕	High	108-114
HEV	◕	✓	●	✓	◕	◕	Medium	98-104
PHEV	◔	(✓)	◕	✓	◕	◕	Medium/low	114-127[3]
Overnight	◔	(✓)	●	✓	●	●[2]	Low	108-121
Opportunity	◔	(✓)	◕	✓	●	●[2]	Low	110-122
Fuel cell	◔	(✓)	◕	(✓)[1]	●	●[2]	Medium	132-151

● High ○ Low ✓ Available (✓) Partly available

1) Capacity not sufficient for whole fleet 2) Renewable electricity, excluding CO2-impact from battery production which is significant 3) PHEV with opportunity charging

Summary of analysis results by technology towards 2020[3]

Based on interviews, it appears that the steps normally taken by PTAs when introducing electric buses are:

1. **Pre-commercial pilot (5-10 buses)**
2. **Smaller commercial tender (15+ buses)**
3. **Large commercial tenders.**

Recommendations going forward to realize the 2020 targets established for Ruter:

- Continued close dialog with the supplier industry, operators and other public authorities is required to monitor developments
- Gain real experience soon from electric powertrain by smaller introduction in Ruter, and thereafter continued with gradual increases
- Ensure that total long-term environmental impact is prioritized
  -A large deployment of the ”second best” renewable option may be the most cost and environmentally effective solution
  -A small scale deployment of the ”best” solution may have lower overall impact

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Acronyms

BTL	Biomass to Liquid
CCS	Carbon Capture and Storage
EU	European Union
EUR	Euro
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester
FC bus	Fuel Cell Electric Bus
GBP	British Pound
g/km	Grams per kilometer
g/kWh	Grams per kilowatt hours
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
OEM	Original Equipment Manufacturer
PHEV	Plugin Hybrid Electric Vehicle
PTA	Public Transport Authority
PTO	Public Transport Operator
PM	Particulate matter
RES	Renewable Energy Source
RME	Rapeseed Methyl Ester
SMR	Steam Methane Reforming
TTW	Tank-to-wheel
TCO	Total Cost of Ownership
TSC	Total Servicing Cost
UK	United Kingdom
UN	United Nations
VAT	Value-Added Tax
WACC	Weighted Average Cost of Capital
WTW	Well-to-Wheel

Renewable Energy Powertrain Options

1. Introduction

This chapter is an introduction to the report and the current renewable energy bus powertrain project in Oslo and Akershus.

1.1 Project background

Urban traffic is a concern for all large cities as traffic causes pollution, noise and health issues. A growing population creates needs for a large scale, efficient and environmentally friendly public transportation system. The Oslo region is one of the fastest growing in Europe and public transport has gained share of motorized transports. As a percentage of motorized journeys made in 2014, Ruter's shares were 42% in Oslo, 21% in Akershus and 33% for the region as a whole[1]. In the future, Oslo and Akershus have decided public transport is to capture all growth in passenger traffic, together with bicycling and walking.

Buses driven by combustion engines are considered a significant contributor of greenhouse gas emissions (GHG) as well as the majority of local emissions (Particulate matter (PM) and Nitrogen Oxides (NOx)) from public transport. Public transport in Oslo and Akershus accounts for approximately 4% of greenhouse gas emissions (GHG) from road transport, of which buses account for a majority[2]. As public transport is to account for an even larger proportion of transportation in the future, the environmental footprint will become larger, and the need for improvement measures are at the top of the agenda for a broad range of stakeholders, including PTAs (Public Transport Authorities).

As a response to increasing regulatory pressures, the European automotive industry has over the last two decades significantly enhanced the environmental requirements regarding local emissions. One key contributor is the EURO emission regulation. The EURO emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The heavy duty emission standards have been introduced to reduce the emissions primarily caused by diesel engines. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. As shown in figure 1, the result from improved engine emission has dramatically reduced PM and NOx pollution

[1] Ruter Annual Report 2013 - [2] Ruter presentation, Ruter's framework conditions, 2015 - [3] Volvo -
[4] European Energy Commission, 2015 - [5] European Union, 2015 - [6] Ruter Annual Report 2013 -
[7] Ruter Electric Conference Presentation, December 2014 - [8] Ruter presentation, Ruter's framework conditions, 2015

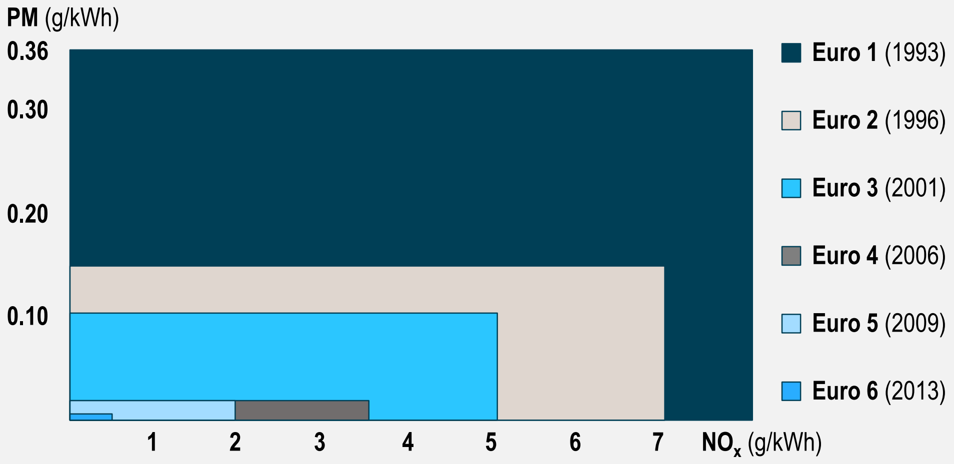


Figure 1: Euro emission requirements [3]

Greenhouse gases (GHG) are not part of the EURO I-VI emission requirements. However, society and customers are increasing the demands on GHG reduction. The European Union (EU) is committed to significantly reducing greenhouse gas emissions and the need for renewable options for public transport is higher than ever before. To monitor progress, the EU has set ambitious targets. By 2020, the EU aims to have 10% of the transport fuel in every EU country to be from renewable sources such as biofuels. The definition of 'renewable' is somewhat debated as the production and transport of some of the biofuels also generate emissions. The EU has therefore launched certain criteria for biofuels in order to consider the whole cycle when analyzing the emissions (well-to-wheel), meaning that extraction, processing and distribution of the fuel are considered[4]. To qualify towards the EU renewable targets, there must be a 35% well-to-wheel reduction in greenhouse gas emissions (CO2) compared to conventional diesel. The requirement increases to 50% in 2017 and to 60% reduction in greenhouse gas emissions in 2018. Further, the raw materials for biofuels cannot be sourced from land with high biodiversity high carbon stock in order to be counted as part of the fulfillment of the renewable energy target[5].

Bus manufacturers have responded to GHG pressures by introducing new technologies for biofuel usage and reduced fuel consumption of fossil fuels, e.g. by new electric powertrains. In parallel, battery technologies have developed significantly. As a result, over the last 10 years, after commercial vehicles and buses have been dominated by diesel, new technologies are chall-enging the dominant power source, diesel. The new technologies are maturing at different paces, and are becoming more operationally and economically relevant.

New alternative powertrains and fuel solutions discussed in this report are:

- Engines using biofuels such as biodiesel, bioethanol or biogas
- Hybrid electric vehicles (HEV) using both an conventional engine and an electric engine
- Plug-in electric vehicles (PHEV) using both an conventional engine and an electric engine
- Fully electric battery vehicles (BEV) using solely an electric engine
- Fuel cell electric buses (FC) using solely an electric engine

1.2 Ruter today

Ruter As began operations on 1 January 2008, following a merger in 2007 of the functions carried out by previous administration companies AS Oslo Sporveier and Stor-Oslo Lokaltrafikk a.s. (SL). The administration company Ruter As is owned jointly by Oslo municipality (60%) and Akershus County Council (40%)[6].

Ruter is responsible for transport services in Oslo and Akershus counties in Norway, serving 1.2 million people. As depicted in figure 2, the area covers more than 20 municipalities and the operating region is a vast area and a large rural region. The distance north to south is about 100 km and the population density is the highest in and near Oslo City. Local temperatures span from -200 C in the winter to +300 C in the summer[7].

Ruter is a not-for-profit public transport authority (PTA). Public transport operators (PTOs) under contract with Ruter carry out the transportation services. In the case of bus and ferry services, contracts are awarded through competitive tenders. Financing for operations of the bus services are via public subsidies, and ticket paying passengers[9].

Figure 2: Oslo and Akershus map[8]

Ruter has about 1100 buses in city and regional traffic including school transportation. There are also some special transports operating in a taxi service fashion. Contracted PTOs are responsible for operations and maintenance of both buses and bus depots. In principle, one operator contract is linked to one depot. Each depot is used for lines linked to the specific contract. Ruter today has 22 contracts and 24 depots.

The maturity profile of contracts and associated buses used on routes linked to contracts, indicates that more than half of buses in daily operations have contracts terminating before 2021 (using 10 years contract length and if all prolongation options are used), see figure 3. This means that contracts representing about 60 % of Ruter's buses will come to an end before 2021, and could be available for powertrain change. For contracts running longer than 2020, there is a clause that these have to use renewable energy after 2020. There could also be possibilities in existing contracts to execute a change order for a new technology type.

Of the city and regional buses, approximately 1000 are in daily traffic, with some additional 10-12% used as back-up (to cover for planned and unplanned down-times). As shown in figure 4, Ruter uses five types of buses:

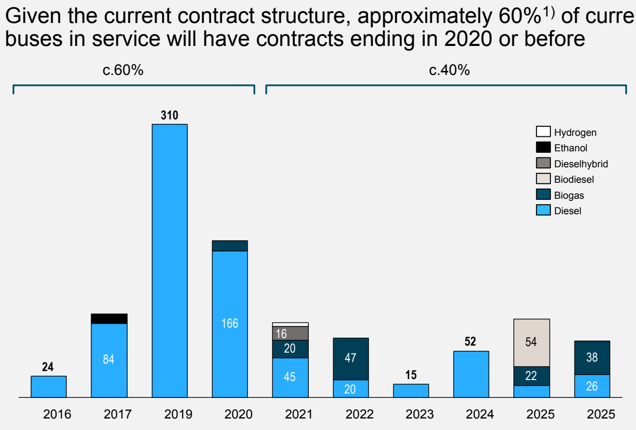
- Standard low floor city bus, c. 12 meter
- Standard low floor city bus, c. 13.7 meter
- Articulated low floor city bus c. 18 meter
- Regional c. 13-15.5 meter bus (Norwegian ' boggy-buss')
- Minibuses 7-10 meter

Ruter today have 22 contracts, operated from 23 depots. Bus services are divided into Region, City and School (the latter part of regional services).From a bus operating perspective, there are more than 100 lines, including lines where buses start on one line and then continue onto another line, so called interlining (from a passenger perspective there are about 150 lines). Ruter uses a combination of fuels, although diesel represents the largest share in 2015 (c. 77%), see figure 4. Approximately 20% of the buses run on biofuels, and a smaller number of buses using hydrogen. Buses used have different compositions of seating and standing passengers:

- Class 1: Often normal city buses with more than 22 passengers, and a high share of standing passengers
- Class 2: Typically regional buses where vehicle mainly aligned with seating for more than 22 passengers, and standing passengers focused to the aisle
- Class 3: Vehicle only intended for seated passengers

Ruter's lines/routes have varying lengths from 3 to c. 70 km for city and regional lines. Lines also vary in topography and Oslo is a city with varying altitude. For each line, there are typically more buses operating in peak hours, of which certain buses only run in peak hours and thereby operate fewer hours and also have a lower average daily mileage. See figure 5 page 14.

Operationally, for both city and regional lines, the waiting time end of route is often zero minutes in both peak shifts and off-peak shifts. This places potential constraints or require adjustments if new technologies are to be introduced, see figure 6 page 14.



1) Excluding special transport and back-up buses (back-up buses c.10-12%)

Source: Route planning team, Frida system

Figure 3: Estimated number of buses by type of fuel where year shown is the contract end date including extension option. Number of buses excludes back-up buses (c. 10-12%)

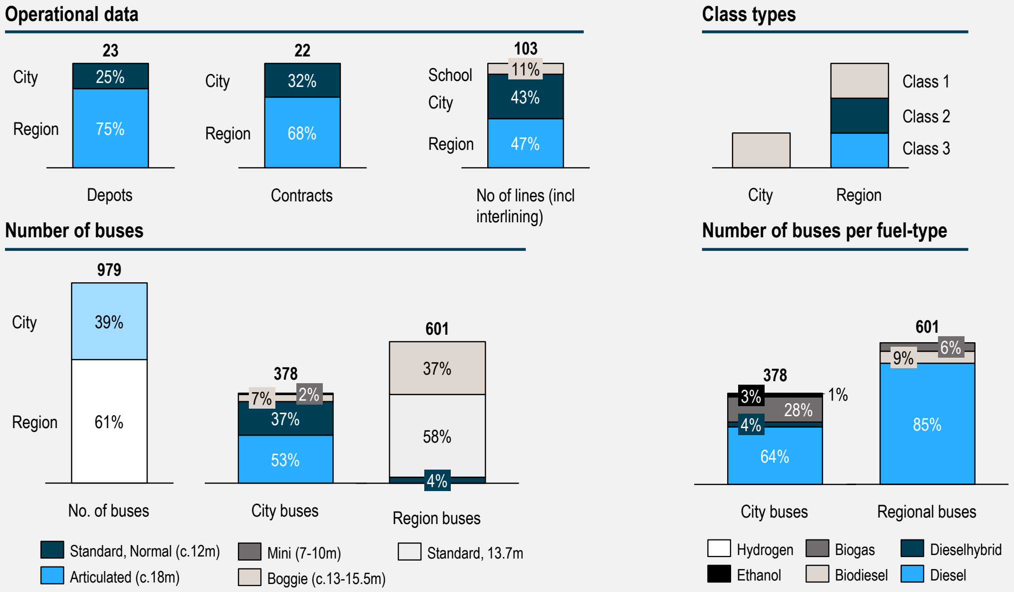


Figure 4: Operational data, class types, number buses by type and fuel

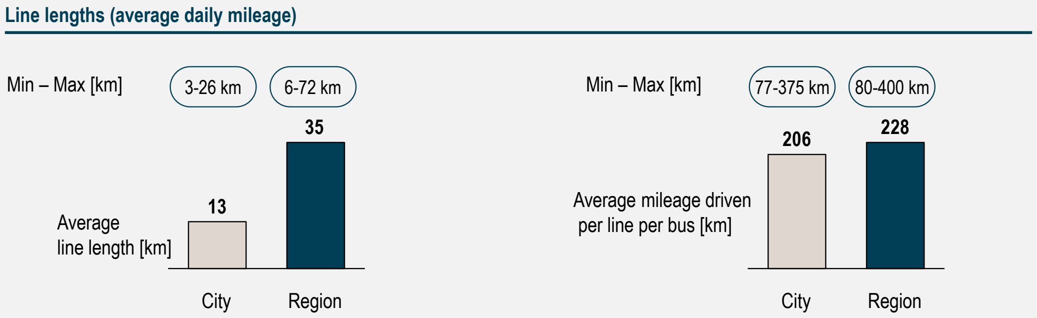


Figure 5: Route lengths in Oslo and Akershus

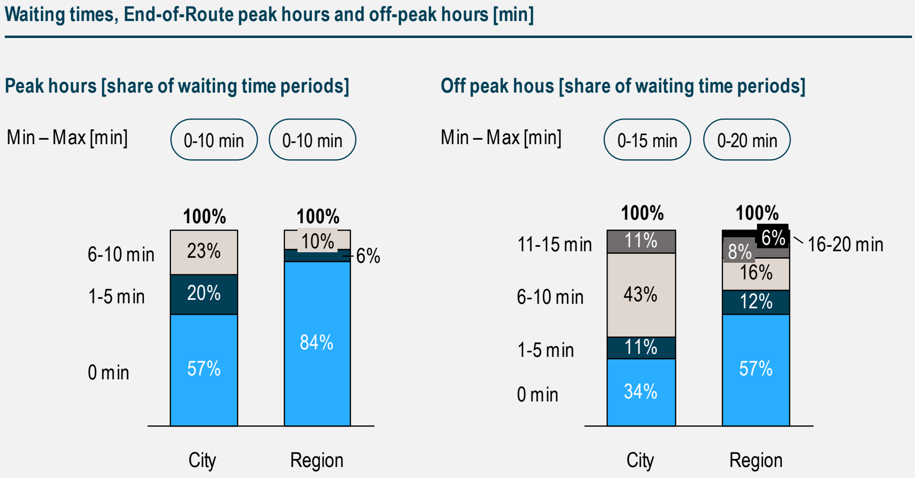


Figure 6: Bus waiting times end of route in Oslo and Akershus (share of lines)

1.3 Ruter's objectives and goals

Due to improved emission regulation via the EURO I-VI, NOx and PM emissions from buses in Oslo and Akershus have declined significantly, as shown in figure 7. Per vehicle km, the reductions have improved at 16 and 25% per annum. Per passenger km, the reductions have improved slightly more as more passengers per km have been transported. As total kilometers have increased, the total emissions (tons) have not decreased with the same magnitude, however reduced significantly none the less. The total, measured in tons, have declined at 15 and 24% per annum. CO2 levels, which are not part of the EURO I-VI emission regulation, have not seen the same annual improvement as other emissions however. To reduce these CO2-levels, more fossil free fuel must be used.

Improving the environment is fundamental to Ruter's business. Ruter's owners, the City of Oslo and Akershus County, have set two important objectives for public transport in the future. The first is that increased passenger traffic demand shall be solved by public transport, bicycling and walking, and the second is to only use renewable energy sources.

In 2020, public transport in Oslo and Akershus must be powered by only renewable energy. This calls for wide-ranging changes, especially to the bus fleet in the region. Ruter's aim is to introduce the most effective long-term solutions as quickly as possible.

Ruter's environmental strategy for the period 2014-2020 establishes that Ruter will:

- In 2020, only use renewable energy sources for all public transports
- Increase usage of biogas
- Test electric buses and ferries

In addition to the targets for 2020, Ruter's most important environmental priorities for the coming 50 years are[11]:

- Increased share of public transport
- Environmentally friendly traffic production
- Environmental certifications and requirements

To achieve climate targets, the Oslo municipality has required that all bus operations by 2020 are climate neutral and that all buses running in Oslo will at minimum meet Euro VI standards. Akershus County has a goal of that transport emissions should be reduced by 20% before 2030.

1.4 Project approach and scope

Ruter is responsible for all types of public transport in the Oslo/Akershus region, however only buses are in the scope of this report. Bus types included are the traditional types; single deck, low-entry 12 and 18 meter buses. Regional buses and some smaller buses are also considered.

Although the technology is mature, commercially available and in use in several cities throughout the world, trolley buses have been excluded from the analysis for the following reasons:

- Large investments required in grid networks
- Not suitable for regional operations as unfeasible to install infrastructure
- Potential conflicts with existing grid infrastructure for trams
- Limitation of route flexibility
- Aesthetic considerations and impact on city scene.

The project as a whole has a larger scope than this report. The report will be used, in combination with input from bus manufacturers, other transport authorities, pilots/trials and operators, as base to

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[10] Ruter Annual Report 2013 - [11] Ruters Environmental Strategy 2014-2020, 2014

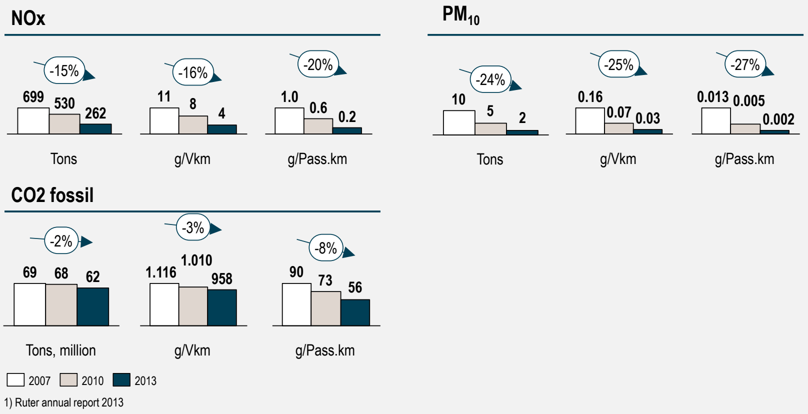


Figure 7: Emissions from buses operating in Oslo and Akershus[10]

develop alternative powertrain fleet scenarios. Different scenarios will be assessed from both financial and operational perspectives and also political ambitions will influence the final bus fleet strategy.

As depicted in figure 8, in order to develop scenarios, the technology capabilities and readiness need to be analyzed. This includes a review and assessment of the most recent developments from reports and studies. In addition, experience form trials and pilots of electric buses as well as information from bus OEMs have been used as input for the analysis.

Technology capabilities & bus OEM readiness
The report focuses on analyses of powertrain developments with respect to technical maturity, environmental impact, operational performance and costs. The report has not specifically investigated other types of efficiency improvements of general bus technology (e.g. light weighting structures, heat recovery or friction resistance improvements) as it is assumed that all types of technologies can benefit from these developments.

Geographical scope for the comparison of available technologies is to a large extent focused on Europe. This includes emerging market players (e.g. from China) present in Europe or with stated ambitions and interest in the European market. There are a number of reasons why the main focus should lie on Europe, e.g. European bus properties/ design, requirement of EU/EC certification etc. Developments of other geographies are commented upon at higher level.

Technology fit
Further, the technology fit towards Ruter is assessed in the report. In particular, this relates to understanding how well a technology fits with Ruter's current operations, link to operator contracts, fuel availability in the local market, infrastructure readiness and availability for Ruter, and finally considerations of the business and ownership model.

Implications for Ruter
The focus of the assessment is primarily on the suitability and implications for Ruter. International comparison has been made with applicability of Oslo and Akershus in mind. The report partly also includes Ruter's strategy, the ambitions of the politicians in Oslo and Akershus. Cost implications have been analyzed on a general level, but with adjustments to the specific situation in Ruter's area of responsibility Understanding of maturity of new or emerging technologies in a context of large scale implementation in 2020 or shortly thereafter (commercial readiness for serial production) has been key.

The hypothesis from Ruter has been that battery electric buses are the optimal solution for the long-term future. Therefore, particular focus has been on understanding other renewable technologies in light of battery electric buses.

The report is based on a number of sources, including

- Existing Ruter inhouse information
- Roland Berger international experience
- Discussions and material from bus OEMs, infrastructure equipment producers, fuel suppliers, operators and consultants.
- Discussions and information from stakeholders in pilots across Europe
- Available reports and studies on alternative powertrains

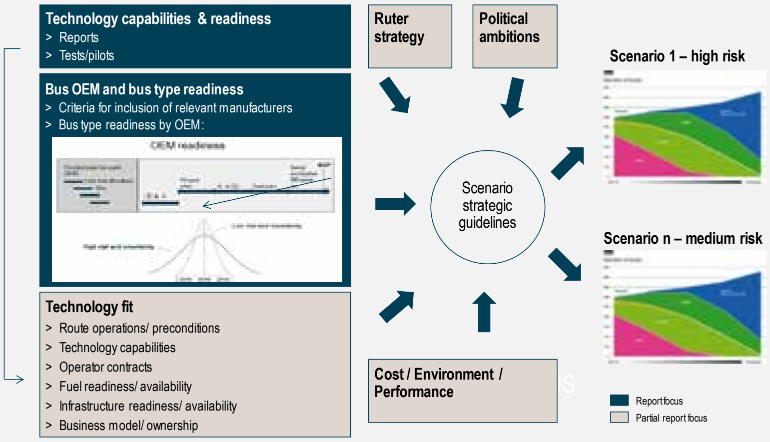
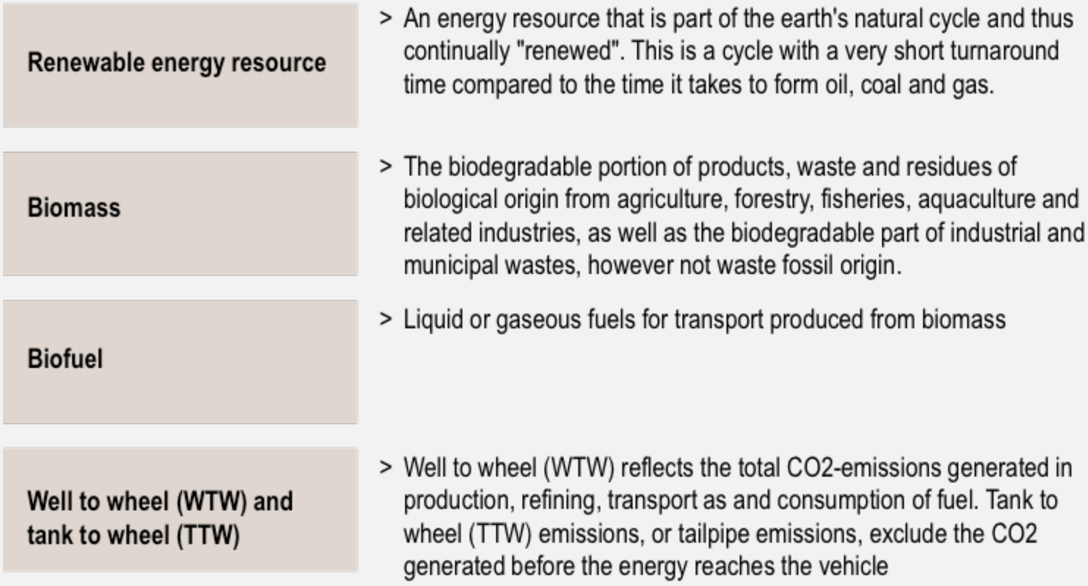


Figure 8: Overview of project and report scope



Renewable energy resource	> An energy resource that is part of the earth's natural cycle and thus continually "renewed". This is a cycle with a very short turnaround time compared to the time it takes to form oil, coal and gas.
Biomass	> The biodegradable portion of products, waste and residues of biological origin from agriculture, forestry, fisheries, aquaculture and related industries, as well as the biodegradable part of industrial and municipal wastes, however not waste fossil origin.
Biofuel	> Liquid or gaseous fuels for transport produced from biomass
Well to wheel (WTW) and tank to wheel (TTW)	> Well to wheel (WTW) reflects the total CO2-emissions generated in production, refining, transport as and consumption of fuel. Tank to wheel (TTW) emissions, or tailpipe emissions, exclude the CO2 generated before the energy reaches the vehicle

Figure 9: Definitions used in report

1.5 Defining scope of fuels and powertrain technologies

Since the definition of renewable energy resource is stricter than fossil free (since it includes more aspects than only fossil free), it is important to be clear on the environmental ambition. The actual environmental footprint of the different powertrain solutions is discussed later in the report.

The report discusses CO2 from a well-to-wheel perspective. Well-to-wheel (WTW) reflects the total CO2-emissions generated in production, refining, transport as and consumption of different fuels. Tank-to-wheel (TTW) emissions, or tailpipe emissions, exclude the CO2 generated before the energy reaches the vehicle. A well-to-wheel perspective enables more accurate comparison of different technologies and more precisely present the total environmental impact of a certain fuel. The well to wheel analysis in this report does not include bus and infrastructure production and is not to be seen as a whole life-cycle perspective with regards to bus manufacturing and infrastructure production. Battery production is included in the CO2-analysis on a discussion basis.

For electric buses, both the production of electricity, as fuel, and electricity storage (battery) there is a need for environmental considerations.

- Electricity can be either renewable or fossil dependent on the way of production, e.g. hydro versus coal based.
- For batteries, it is highly important that the storage and recycling of spent batteries are appropriate and conducted in an environmentally friendly manner. Since scarce metals in batteries (such as lithium) are not consumed in the batteries, a sustainable process for re-using and recycling batteries makes battery buses a renewable powertrain option.

Important facts

- The diesel engine (Internal Combustion Engine, ICE) is the prime engine type for buses all around the world and only a small percentage of buses worldwide use alternative fuels such as biogas, biodiesel, ethanol or electricity
- Energy density and powertrain efficiency are important to combine when analyzing powertrain options
- First generation biofuels are fuel produced from agricultural crops. Second generation biofuels are produced from non-food cellulosic biomass e.g. agriculture or organic waste
- Biofuels from various feedstock differs with regards to life-cycle (well-to-wheel) CO2-emissions
- Hybrids utilize both an ICE and an electric engine and are considered an attractive bridging technology towards zero emissions
- There are two main types of battery charging systems available for urban electric buses, overnight charging and opportunity charging
- Overnight charged buses have significantly larger battery capacity than opportunity charged buses and are only charged in bus depots
- Opportunity charging is carried out either by inductive or conductive technology and enables charging during the bus route

2. Technology landscape

This chapter will provide a descriptive overview of the different powertrains supporting infrastructure and fuel solutions available today for renewable energy bus technologies. A broad approach is taken in this chapter and no potential alternatives are ruled out. See Important facts.

2.1 Introduction

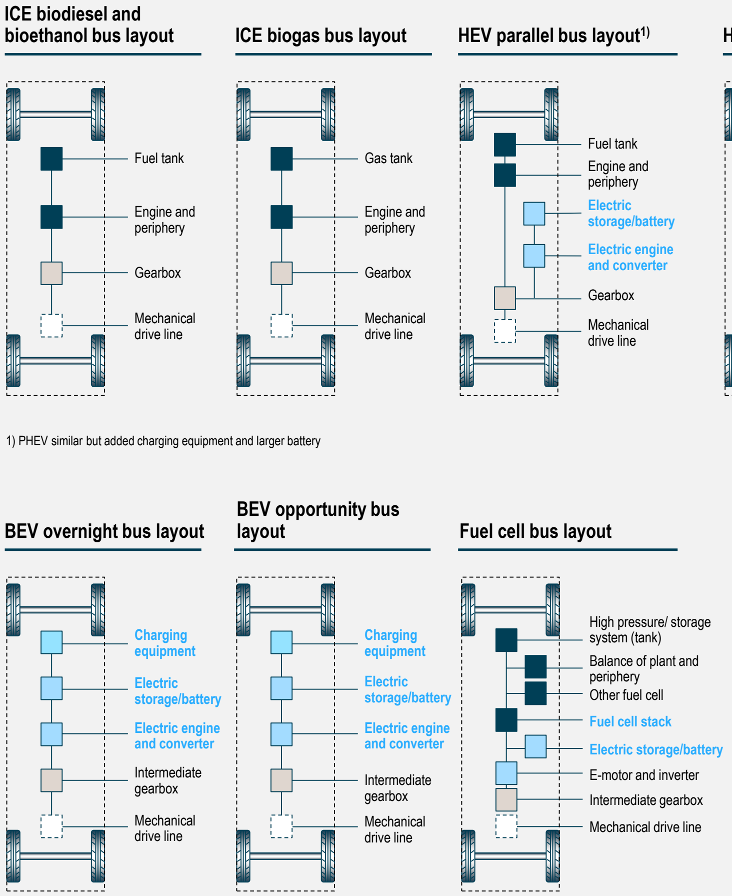
The diesel engine (Internal Combustion Engine, ICE) is the prime engine type for buses all around the world and is widely used due to superior energy density and high reliability. The main fuel used is conventional fossil diesel. Only a small percentage of buses worldwide use alternative fuels such as biogas, biodiesel, ethanol or electricity (mainly trolleybuses).

The diesel engine has drawbacks. The downsides of engines powered by conventional diesel are high emissions of both particles matter (PM), nitrogen oxides (NOx) as well as greenhouse gases, high noise levels and usage of fossil resources. Although diesel engines are becoming much more fuel efficient and the PM and NOx-levels have been significantly reduced, there is still a need of further reducing usage of fossil diesel. Based on Ruter's target of only using renewable energy in 2020, the relevant alternative powertrain types (shown in figure 10 page 20) that will be described and analyzed in this report are:

- ICEs using biofuels, we consider three types: biodiesel, bioethanol or biogas
- Hybrid electric vehicles (HEV), serial or parallel
- Plug-in hybrid electric vehicles (PHEV), serial or parallel (larger batteries than HEV)
- Fully electric battery vehicles (BEV), overnight or opportunity (larger batteries than PHEV)
- Fuel cell electric buses (FC)

Other alternatives, such as trolley buses, have been considered less relevant and therefore ruled out. See figure 10 page 20.

The alternative powertrains (to fossil diesel) differ in maturity. Biofuels, such as biodiesel, biogas, and bioethanol, can be used in a conventional diesel engine with some modifications. Therefore, the step towards using biofuels is relatively short. However, biofuels still emit local emissions and greenhouse gases (GHG), although in reduced amounts, and many argue that electric driving will be needed in order to reach local environmental targets in the future. Hybrid buses are powered by both a conventional diesel engine and an electric engine. Fully electric buses and fuel cell buses, driven solely by an electric engine, have zero local emissions and no tailpipe GHG-emissions and are favorable from an environ-mental aspect. These buses are however not fully commercially ready and in the process to be intro-duced at a larger scale. It is, however, also of great signifi-



1) PHEV similar but added charging equipment and larger battery

Figure 10: Schematic powertrain overview

cance how the electricity consumed is produced, whether it is from renewable sources or not.

Energy density and powertrain efficiency are important to combine when analyzing powertrain options. Different fuels vary in terms of energy density (energy relative volume) and powertrains differ in energy efficiency (fuel consumption per km). The differences have high impact on important operational parameters such as driving range and passenger capacity. Energy density is important since there are both volumetric and weight restrictions on a bus. Hence, low energy density means more fuel volume needed on the bus, less driving range and optionally less passenger capacity.

An electric battery driven bus must have a battery pack that weighs about 8-10 times more than the equivalent amount of diesel. The energy density is about 25-35 times higher in diesel than in an electric battery. Figure 11 page 21 shows the energy density for various transportation fuels. The figure illustrates that batteries are heavier than diesel and requires more space.
When comparing a diesel engine with an electric engine, there is a huge difference in energy efficiency. A diesel engine has approximately c. 30-35% efficiency (mainly heat losses) and an electrical engine has approximately c.90% efficiency. This means that there is a significant increase in weight when changing from diesel to battery as a main power source.

[12] Source: U.S. Energy Information Administration, 2012 - [13]Source: Study analysis

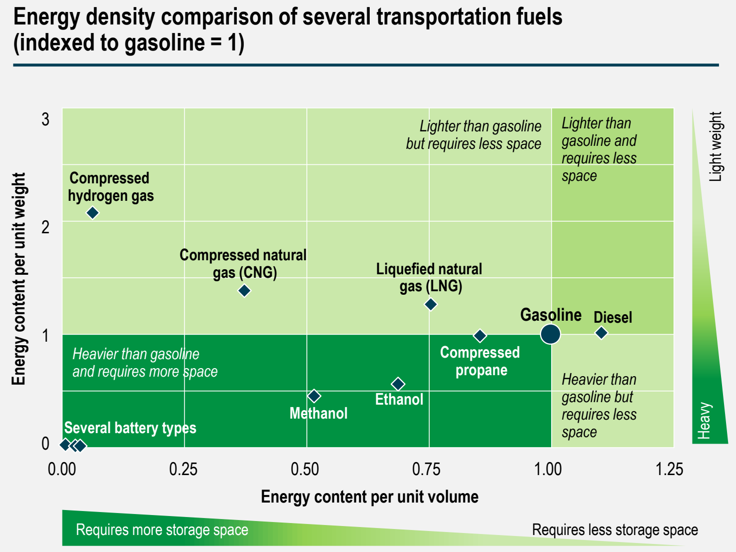


Figure 11: Energy density comparison of several transportation fuels[12]

		Engine	Potential renewable energy source to 2020[1]	Renewable 2020 for Ruter	Electric
Biofuels	**Biodiesel - ICE** (2nd generation)	ICE	B100 from oils, organic waste, cellulosic feedstock etc.	☑	☒
	Bioethanol - ICE (2nd generation 95%)	ICE	ED95 or E95 from cellulosic feedstock etc. (c.95% renewable)	☑	☒
	Biogas - ICE	ICE	Agricultural waste, manure, plant material, food waste, sewage etc.	☑	☒
Electric	**Hybrid – HEV2) (parallel or serial)**	ICE + Electric	Biodiesel/bioethanol/biogas + Green electricity	☑	☑
	Hybrid – PHEV2) (parallel or serial)	ICE + Electric	Biodiesel/bioethanol/biogas + Green electricity	☑	☑
	Electric Vehicle - Overnight	Electric	Green electricity, i.e. wind or water power	☑	☑
	Electric Vehicle - Opportunity	Electric	Green electricity, i.e. wind or water power	☑	☑
	Electric Vehicle - Fuel cells	Electric	Hydrogen	☑	☑

1) Biofuels according to EU requirements of 60% CO_2 reduction by 2018
2) HEV = Hybrid Electric Vehicle, PHEV = Plug-in Hybrid Electric Vehicle, EV = Electric Vehicles

Figure 12: Powertrain overview[13]

Below is a table that covers possible powertrain solutions for Ruter's renewable energy target for year 2020, including biofuel-driven ICEs as well as different types of electrical powertrains, see figure 12 pge 21. For fully electric vehicles and hybrids, it is important to use fossil free produced electricity in order for the powertrain option to be renewable. Hydrogen needs also to be produced from fossil free feedstock in order to fulfill the requirements (electricity from renewable energy sources). Later in the report, these alternative powertrain solutions will be analyzed in more detail.

All powertrains in figure 12 are considered potential renewable options for Ruter in 2020.

2.2 Biofuels in a conventional Internal Combustion Engine (ICE)

An internal combustion engine (ICE) is an engine where the fuel combustion occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. The most recent diesel ICEs with Euro VI standard, have advanced technology for filtering emissions using various catalytic converters and injection of diesel exhaust fluids such as AdBlue. AdBlue is a high purity urea solution used to reduce emissions of oxides of nitrogen from the exhaust of diesel vehicles. An ICE can be powered by both fossil diesel and biofuels.

Biofuels are renewable liquid of gas transport fuels derived from biomass. The term biofuels includes a number of different fuel types differentiated by the source material, manufacturing process and type of fuel ultimately created. The most commonly used biofuels are biodiesel, biogas and bioethanol.

2.2.1 Different generations of biofuel

Today, biofuel is an imprecise term of various products with different origins and different end-use properties. A common categorization is by first, second and third generation biofuels. However, the terminology is not fully established.

First generation biofuels are fuel produced from agricultural crops. Second generation biofuels are produced from non-food cellulosic biomass e.g. agriculture or organic waste, see figure 13. Third generation of biofuel is based on algae and it is considered highly interesting. However third generation is still in an embryonic development phase and far from serial production.

The only time crops can be categorized as second generation biofuels are if they have already fulfilled their food purpose. As an example, waste vegetable oil is a second generation biofuels because it has already been used as food and is no longer fit for human consumption. Virgin vegetable oil however, is considered a first generation biofuel[15].

A brief comparison between the different biofuel generations is presented in figure 14. First generation biofuels are commercially available and economically viable. See chapter 3.4 for a more detailed analysis regarding first and second generation biofuels. Third generation biofuels are not assessed further due to low commercial availability expected before 2020.

Biofuels from various feedstocks differs with regards to life-cycle (well-to-wheel) CO2-emissions. An adequate comparison of biofuels require good knowledge about the origin of the feedstock, the production process and the transportation specifications of the vehicle since there can be GHG-emissions in all biofuel production steps. In general, second generation biofuels are more beneficial than first generation biofuels from an environmental perspective. Please refer to chapter 3.4 for an in-depth assessment of fuel emissions

1st generation	**From food crops.** First-generation biofuels rely on crops that have readily accessible sugars, starches and/or oils as their feedstock, such as corn, soy, palm, rapeseed and sugarcane. Production of biofuels involves either fermenting the sugars or transesterfication of fatty oils.
2nd generation	**From non-food crops.** Second-generation biofuels use lignocellulosic biomass as feedstock, and can use forest and agricultural production wastes, such as corn stalks, as well as dedicated biofuel crops like switchgrass. The fuel is made by using enzymes/microorganisms to break down the cellulose into sugar, or by using a thermochemical route.
3rd generation	Third-generation biofuels have often been defined as algae biofuel.

Figure 13: Biofuels generation overview[14]

	1st GENERATION	2nd GENERATION	3rd GENERATION
TECHNOLOGY	Economical and well established	Technology in development – relatively high production costs	Technology in development – advanced technology, high investment
FEEDSTOCK	**From food crops**: Rapeseed, wheat, soybean, starch, sugar etc.	**From non-food crops**: Cellulosic biomass (agriculture & organic waste, straw), used oil & fat etc.	Algae biomass
PRODUCTS	Bioethanol, biodiesel (FAME or RME), biogas	HVO, BTL, Synthetic fuels produced via gasification	Algae oil (oilgae)
LEVEL	Commercial	Commercial / R&D	Research and technology development
ADVANTAGES	Environmentally friendly, economical	Non-competitive with food, Environmentally friendly	Low input, high-yield feedstock
PROBLEMS	Limited feedstocks (food vs. fuel), winter capabilities, blending regulation	High cost of prod. compared to 1st gen., infrastructure development	Process optimization, scale up, high investment

Figure 14: Biofuels - generation comparison[16]

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[14] Source: Study analysis - [15] Biofuel.org, 2015

and environmental impact.

2.2.2 Biodiesel supplying an Internal Combustion Engine (ICE)

There are various bus manufacturers supplying diesel engines that can utilize both fossil diesel and pure bio-diesel (B100) without a significant cost increase. For example Scania offers two Euro VI 9-liter engines and two Euro VI 13-liter engines that could run on 100% biodiesel. Low blends of biodiesel (blended with conventional diesel) can in general be used in conventional diesel engines. Pure bio-diesel however, often requires some modifications in the engine depending on the type of biodiesel and feedstock used.

Pure biodiesel is called B100. A biodiesel called B30 has 30% biodiesel and 70% fossil diesel. 100% biodiesel is referred to as B100 and only this pure form of biodiesel is fossil free.

The different biodiesel first generation production methods differ in maturity. First generation FAME-based biodiesel is normally produced by using a transesterification process where a glyceride reacts with an alcohol in the presence of a catalyst, forming a mixture of fatty acids esters and an alcohol. The most commonly used alcohol is methanol. The standard methanol used is based on natural gas (fossil) but it is possible to use renewable methanol as well.

Second generation biodiesel is made of non-food crops such as waste cooking oil, animal fat or cellulosic feedstock and can also be referred to as advanced or synthetic biodiesel. Synthetic biodiesel can also be made from other chemical processes but must be made from an organic matter in order to be categorized as a biofuel. Because second generation biofuels are derived from different feedstock, different technology must be used to extract energy from the biomass. Two common processes are called Hydro-treating (used for manufacturing Hydrotreated Vegetable Oil (HVO)) and Biomass-to-Liquid (BTL). HVO and BTL are high-quality paraffinic diesel production methods less mature than FAME but with chemical and physical properties more similar to fossil diesel.

The HVO-process is a conversion of fatty acids to fuels by adding hydrogen to the process. BTL-biofuel is produced by gasification of biomass, such as waste wood, into a synthetic gas. This is then converted to biodiesel using a process called the Fischer-Tropsch (FT)-process. The hydrogenation process to produce HVO is considered the most cost effective process currently available to produce advanced biofuels.

FAME-biodiesel can slightly increase the service level of the engines due to the fact that bio-diesel is organic and may contain some water, which can cause malfunctions in the engine. Also, FAME-biodiesel is not compatible with all kinds of hoses and gaskets and may soften and degrade certain types of rubber compounds in these and thereby cause them to leak[17]. Since HVO and BTL biodiesel have chemical and physical properties more similar to fossil diesel, these fuels are better than FAME with regards to engine service need.

Different biodiesel types have different cold weather properties. In countries with cold climates like Norway, pure FAME-biodiesel can become waxy at below zero temperatures[18] and is less suitable at temperatures below -15 degrees C. Different feedstock have different cold weather properties. Canola, sunflower and corn have good cold weather properties whereas palm and coconut-based oils have the worst[19]. Second generation synthetic biodiesel has better cold weather performance compared to first generation biodiesel and according to three suppliers in the Nordic countries[20], HVO can be used all year around.

Additives used in FAME during wintertime are normally not fossil free. The solution to operate on FAME-based B100 during winter time is to use additives that can increase the winter operability by modifying the wax crystal structure when cooling occurs. The additive must be added to the fuel before it reaches the cloud point temperature (temperature where wax crystals first appear) to be effective. There are different kinds of additives that need to be tested and verified with the kind of B100 currently in use. A commonly used component in the additive is Kerosene. Kerosene is however not fossil free since it is a liquid formed from hydrocarbons obtained from the fractional distillation of petroleum and additives should be analyzed from both a fossil and toxic point of view.

The infrastructure for biodiesel is filling stations at the bus depots and the infrastructure is in most regards the same as for conventional diesel. However, since FAME-biodiesel freezes at higher temperatures than conventional diesel, this must be taken into account. Tank, hose and supply line must all be stored at a certain temperature. 4° to 7° C is fine for most FAME-biodiesel, although some biodiesel fuels may require higher storage temperatures[21].

[16] Source: Roland Berger - [17] Biodiesel.org, 2015 - [18] World Bus and Coach Manufacturer Report, 2014 - [19] National Biodiesel Board, 2014 - [20] Interviews with Preem, Neste Oil, UPM, 2015 - [21] Biodiesel.org, 2015

2.2.3 Bioethanol supplying an Internal Combustion Engine (ICE)

Bioethanol as a fuel differs significantly from conventional diesel and require a different engine technology than a diesel motor regarding heating value, self-ignition temperature, vaporization characteristics, and boiling point. Bioethanol also has a low cetane number, which means low ignition performance. Pure ethanol as such will therefore not ignite in a conventional diesel engine[22] [23]. Low blends of bioethanol do not require modifications of the diesel engine however, and proportions of about 10% or less bioethanol can be used in a conventional diesel engine. Proportions of more than 10% bioethanol can cause corrosion in certain parts of a conventional engine and high blends of bioethanol (E85, E95, and ED95) therefore require modifications of the engine. The modifications of diesel engines for ethanol-use include e.g. increased compression ratio and a special fuel injection system[24]. Today Scania is the only bus manufacturer with commercially available bioethanol buses[25].

Pure bioethanol can be used as fuel but is not fossil free. Bioethanol is an alcohol made by fermentation of bio-mass with high carbohydrate content. Today, bioethanol is usually made from starches and sugars but can also be made from cellulose and hemicellulose fibrous material. Bioethanol can be used as a blended component or in pure form. Two commonly used kinds of bioethanol are E85 which is 85% ethanol and 15% gasoline and ED95 (or E95), which is 92-95% ethanol and 5-8% alcohol additive for ignition improvement characteristics. One of the most used bioethanol brands is Etamax D, which is produced by the Swedish company SEKAB. Etamax D contains 92% pure bioethanol, 5% ignition improver (poly-ethylene-glycol derivative from Akzo Nobel), 2.8% denaturants and 0.2% corrosion inhibitor additive. These additives are not solely fossil free[26]. Ruter today use ED95 from Borregaard in Norway, made from forestry feedstock.

High blends of bioethanol require separate tanks and pump systems but the infrastructure is in general the same as for biodiesel. Bioethanol can be stored in a regular diesel tank and does not need additional storage capacity[27].

2.2.4 Biogas supplying an Internal Combustion Engine (ICE)

A gas engine is an internal combustion engine, which runs on a gas fuel such as biogas or natural gas. A gas engine uses sparking ignition instead of compression ignition, and a biogas engine has the same technology as a CNG (Compressed Natural Gas) engine and can be powered by both biogas and natural gas. Biogas needs to be stored in several tanks on the bus that are capable of holding the fuel under very high pressure and withstand impact in an accident. On low floor buses the only place to put the tanks is at roof level. When fully filled, a typical set of tanks weighs well over one ton[28].

Biogas is produced by biological material, for example agricultural waste, manure, plant material or food waste that is digested by anaerobic micro-organisms in a tank with no light or oxygen. The digestion process produces methane and carbon dioxide – the biogas. The gas is then transported from the gas storage/tanks (in liquid or gas form) and is cleaned to be suitable for usage as fuel. Liquid biogas will be converted to compressed gas before fueled into the bus. In contrary to natural gas, biogas is produced by renewable sources and therefore fossil free[29].

Biogas and CNG requires expensive refueling infrastructure because the gas has to be pumped at high pressure in to the bus. There are two methods available: a fast-fill process that takes little longer than filling a diesel bus and a slow-fill process where each bus is coupled to a ring main gas pipe in a depot and is slowly filled[30].

2.3 Hybrids – A combination of an electric and internal combustion engine

Hybrids are considered an attractive bridging technology towards zero emissions. Hybrid electric vehicles (HEV) combine an Internal Combustion Engine (ICE) with an electric engine. The ICE can use biofuels such as biodiesel or biogas. Hybrids are characterized by which engine configuration that is physically connected to the drivetrain; usually in either serial or a parallel configuration.

Hybrids that can be externally charged by plug-in connections are called Plugin Hybrid Electric Vehicles (PHEV). PHEVs have larger batteries and an increased pure electric driving range compared to HEVs[31]. They can be operated either by only recharging them with electricity at the depots with conventional plug connections. In such cases, buses need to return several times a day to the depot to be recharged and make use of their plug-in capability. Nevertheless, their driving on electricity only is still limited (up to 40% of km

[22] Advanced Motor Fuels, 2015 - [23] VTT, 2014 - [24] Advanced Motor Fuels, 2015 - [25] Scania, 2015 - [26] Interview with Sekab, 2015 -
[27] World Bus and Coach Manufacturer Report, 2014 - [28] World Bus and Coach Manufacturer Report, 2014 -
[29] Sør-Trøndelag Fylkeskommune, 2014 - [30] World Bus and Coach Manufacturer Report, 2014

driven). As an alternative, plug-in hybrids can also be charged while driving outside the depot using opportunity charging stops at end points of routes. In such cases, driving on electricity only is possible to a far larger extent (→75% of km driven).

HEVs use the ICE as the main power generator. The electric engine is partly used, which usually leads to a fuel consumption reduction of about 20-30% compared to using only a conventional diesel engine. The combination of an ICE and electric engine gives both reduced energy consumption and reduced local emissions without losing flexibility.

A parallel hybrid has a mechanical connection to the driveline with both an electric engine and an Internal Combustion Engine (ICE), see figure 15. Due to the parallel system, both the electric engine and the ICE can provide power during acceleration. Therefore the engines can be downsized compared to the engines in a serial powertrain (and conventional diesel engines). The electric motor provides power at starts and stops and at low speeds. Recent development called "Arrive & Go" enables the bus to only operate in electric mode when arriving to and leaving bus stops. This brings a possibility for inhouse bus stops. Electric drive enables zero local emissions and reduced noise for passengers near bus stops[32].

Parallel hybrid buses have regenerative braking meaning that energy produced when descending a hill or decelerating are fed back to the energy storage system/batteries. Since both the ICE and the electric engine can be utilized to power the vehicle, a parallel configuration enables more power compared to a series hybrid configuration during most operating conditions.

In a serial hybrid all power goes through the electric engine and therefore the engine needs to be larger than in a parallel configuration. The ICE in a serial powertrain does not have mechanical contact with the drive wheels and all the energy produced by the engine is converted to electric power by a generator that supplies electricity to propel the vehicle and to feed the battery[34], see figure 16.

Serial hybrid configurations also have regenerative braking meaning that energy produced when descending a hill or decelerating is fed back to the energy storage system, leading to reduced fuel consumption. One of the main advantages of a series hybrid is that the engine and vehicle speeds are decoupled. Because of this, the engine can run at its optimum speed almost all the time and thereby reduce fuel consumption.

HEV buses do not require additional infrastructure compared to corresponding pure biofuel ICEs. However, PHEVs need additional infrastructure for the electrical charging. Please see next chapter for overview of different charging solutions.

[31] External battery charging is presented in next chapter - [32] World Bus and Coach Manufacturer Report, 2014 - [33] Source: Roland Berger - [34] Select Engineering Services (SES), 2012 - [35] Source: Roland Berger

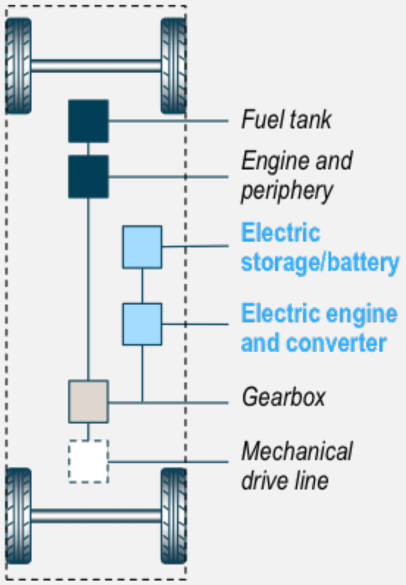

Figure 15: Parallel hybrid powertrain overview [33]

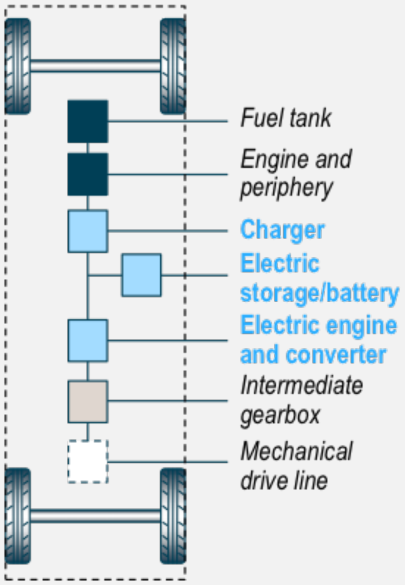

Figure 16: Serial hybrid powertrain overview [35]

2.4 Fully electric powertrains

Electric buses receive energy from an external power source that charges batteries. The batteries then supply the electric bus engine with energy. Today there is no large scale commercial production of electric buses targeted for the European market, however relatively large scale usage of electric buses exists in China. In Europe, there are several ongoing pilots and trials of overnight charged buses, opportunity charged buses and fuel cell buses.

Electric engines have fewer mechanical parts than conventional engines, meaning there is less wear and tear and potentially longer expected lifetime. Reduced wear and tear also lowers need for maintenance. However, costs for maintenance increases in electric buses from potential replacement needs of batteries. Please see later chapters on battery technology and maintenance costs.

2.4.1 External battery charging infrastructure

There are both automatic and manual external charging possibilities for electric buses, see figure 17. Charging can be made either by induction (contactless system using electromagnetism) or by conduction where the bus has physical contact with the charging unit. Electric buses are in general tailored to the line/route they are intended to serve, particularly with regards to battery capacity.

There are two main concepts of battery charging systems available for urban buses, overnight charging and opportunity charging. Fully electric buses today tend to be designed towards one of the ends of the spectrum; either larger battery packs with focus on overnight charging and limited or no charging during the day, or smaller battery packs that are frequently charged during the day at bus stops and/or end stations, see figure 18. Both electric bus concepts require new and comprehensive infrastructure. The charging stations at both depots and end stations need to have sufficient electrical power to charge within the time constraints of the operator.

Overnight charged buses have significantly larger battery capacity than opportunity charged buses. Overnight charged buses are equipped with large battery capacity (→200 kWh) normally utilizing the Li-ion batteries (Lithium Iron Phosphate, LFP). The driving range is limited by the number of batteries carried and a typical driving range for overnight buses is 100-250 km. A challenge for overnight buses is high battery weight, which impacts the passenger capacity as of the bus. Also, the bus purchase price is significantly higher.

Overnight charging takes place while the bus is stationed at the depot. A depot charging system can look as per figure 19 (where a Direct Current

	INDUCTIVE	**CONDUCTIVE**		
		Plugin	**Pantograph**	**Inverted Pantograph**
				
Type	*Automatic*	*Manual*	*Automatic*	*Automatic*
Application area	• *Opportunity*	• *Overnight, Opportunity, PHEV*	• *Opportunity*	• *Opportunity*
In-/Output1)	• *DC* • *60-300 kW*	• *AC or DC* • *10-200 kW*	• *DC* • *100-450 kW*	• *DC* • *100-450 kW*
Main suppliers	• *Bombardier* • *IPT Technology*	• *Several*	• *ABB*	• *Oprid, Siemens, ABB*

1) Indicating typical charger output ranges; ultra-fast charging solutions with higher charging power are under development

Figure 17: Key charging technologies overview [36]

(DC) converter is placed centrally) and each bus is connected to the converter. Alternatively, the converter is in the bus, and then a regular 380 V 3-phase plug is used.

Opportunity charging enables charging during the bus route. When the electric bus charges batteries during the day, normally at end-stations, the battery capacity can be reduced. This electric bus type is called 'opportunity bus'. The driving range is relatively short compared to overnight charging, the driving range is c. 7-20 km[39] after 2-8 minutes of opportunity charging. The range can be extended with longer charging times and/or higher charging power. Alternatively, there are also flash charging concepts being piloted (e.g. 15 seconds charging at each stop). Opportunity charging is carried out either by inductive or conductive technology.

Inductive charging is a contactless system with no physical contact between the source of energy and the bus. The bus parks (e.g. at a passenger stop) above a charging unit (placed below the road surface) that transfers electric current magnetically to the bus batteries.

Conductive charging requires the bus to be physically connected to a static recharging unit, for example either automatically through a pantograph collector placed on the top of the bus[40], or manually through a plugin. A pantograph solution is illustrated below in figure 20. To the left is a cabinet of an AC/DC converter, linking the power from the grid to the pantograph. This can be located away from the pantograph. The pantograph in figure 20 is inverted and lowered towards the bus. Opportunity buses are in general also charged during the night in order to be fully charged in the morning.

Average dimensions for battery size and charging power. An average overnight bus battery is today about 300 kWh and an opportunity bus battery is about 100 kWh. A PHEV usually has a battery of about 50 kWh. For all types high variations can be observed as an actual bus design for an individual trial is normally optimized for specific operational demands. The average charging power for conductive charging is c. 300 kW and for inductive charging up to 200 kW. Overnight depot charging is normally up to 50 kW and PHEV depot charging is less, c. 20 kW[42] .

Further charging discussions regarding standardization of charging system, technology and communication protocols are presented in chapter 3.3.2.

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[36] Source: Interviews, desk research - [37] Source: Interviews, desk research - [38] Source: ABB - [39] Hybricon – Umeå trial and Volvo – Gothenburg trial – [40] World Bus and Coach Manufacturer Report, 2014 - [41] Source: Siemens and Heliox – [42] Interviews

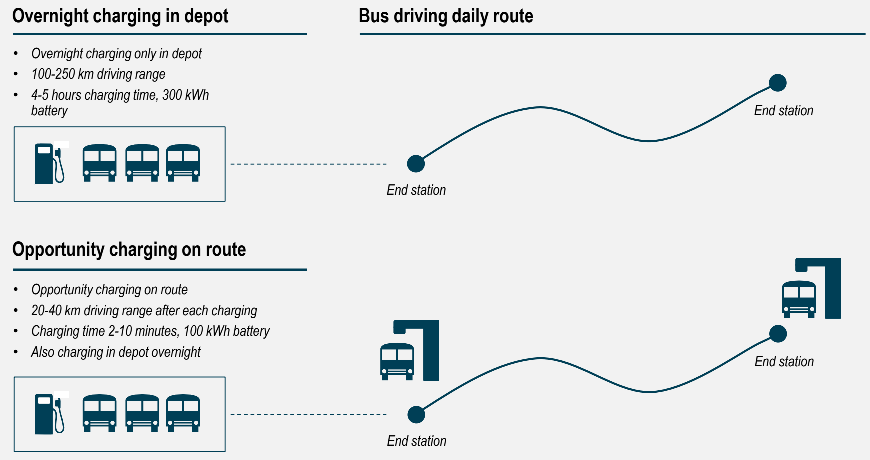

Figure 18: Key charging technologies overview and typical configurations [37]

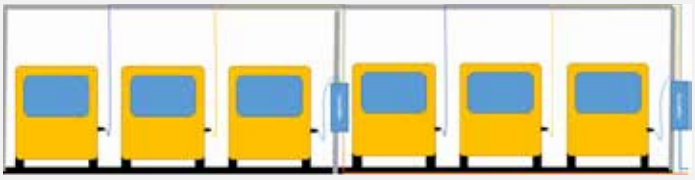

Figure 19: Depot/Overnight charging system [38]

Figure 20: Inverted pantograph charging [41]

2.4.2 Battery technology

Battery electric buses were introduced more than a decade ago and these buses were usually small (approximately 10-15 passengers) and mainly used for very specific services and bus lines with short distances. However, with improved battery technology, battery electric buses are becoming technically and commercially feasible .

Passenger vehicles have been in the forefront of battery development historically due to significant larger volumes. Commercial vehicles, including buses, typically have higher requirements on economics and performance. When analyzing batteries for bus charging, there are some important parameters impacting the battery characteristics, e.g. battery energy content, number of charging cycles, life-expectancy, weight, safety & environmental aspects, reliability and cost.

Different kinds of lithium-ion batteries are the most commonly used battery type for electric buses. The different types are relatively similar but use different anodes and cathodes. Recent technology and cost improvements make Li-ion an increasingly attractive technology for automotive applications. Li-ion batteries were introduced in 1991 by Sony and functions by lithium-ions moving from a negative electrode to a positive electrode during discharge, and moving back when charging.

Li-ion batteries can be tuned for different types of applications. In hybrid applications, the battery focus usually is on high power density (short power support at start/stop) whereas emphasis for pure battery electric vehicles in general is on energy density (increased range).

There are five key groups of relevant batteries for commercial buses, see figure 21. For buses, the two key types used are LFP and LTO.

Lithium iron phosphate (LFP) is one of the most used battery types for electric vehicles because it is considered safe (high electro chemistry stability even at high temperatures) and more environmentally friendly than the other types . LFP batteries are known as energy batteries. The life expectancy is also considered high, although interviews suggest it is reasonable to assume that battery replacement is needed after 5-7 years of use.

The lithium–titanate battery (LTO) has the advantage of being faster to charge than other lithium-ion batteries, see detailed description in appendix. LTO batteries are known also as power batteries, since the charging is fast, the lithium titanate is suitable for opportunity charging and the LTO battery has more charging cycles than the lithium-ion cathode batteries. A disadvantage of lithium-titanate batteries compared to Li-ion cathode types are lower energy density. Interviews suggest that LTO batteries have slightly better life expectancy than LFP batteries.

Other relevant battery technologies are NiMH (Nickel–metal hydride), NiZn (Nickel-zinc) batteries and super capacitors. These technologies are legitimate contenders but not yet proven for large scale use. Super-capacitors or ultra-capacitors have a low energy density but a high power density. Capacitors store energy in an electrostatic field rather than as a chemical state as in batteries and can be charged and discharged in seconds. Since the expected life-time is high (more than 500,000 cycles), super-capacitors are suitable when high power density and high cycle numbers are needed rather than high energy density.

Battery characteristics differ between manufactures. Battery cells from different manufacturers have widely varying properties even if they belong to the same group of lithium batteries. This is because manufacturers use various additives that affect

Type	Material	Abbreviation
Lithium-Ion Cathode	Lithium Cobalt Oxide	LCO
	Lithium Manganese Oxide	LMO
	Lithium Iron Phosphate	LFP
	Lithium Nickel Manganese Cobalt Oxide	NMC
Lithium-Ion Anode	Lithium Titanate	LTO

Figure 21: Overview of key Lithium-Ion battery types[44]

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[43] VTT, 2012 - [44] Source: Study analysis, interviews - [45] Interviews - [46] Interviews

battery cell properties and production quality also affects the cell properties to a large extent .

Further battery development discussion and comparison between different batteries is presented in chapter 3.2.1.5.

2.4.3 Fuel cells

Fuel cell buses are built on conventional chassis and contain a fuel cell system and an electric battery which form the heart of the powertrain, thereby making a fuel cell bus (FC bus) a variant of an electric bus, see figure 22. A FC bus contains the same powertrain as a battery bus, but also features a fuel cell system which is continuously producing electricity to charge the battery and power the electric motor. A fuel cell system typically consists of auxiliary components (humidifier, pumps, valves, etc.) grouped together as part of plant and a fuel cell stack which is made up of bipolar plates and membrane electrode assem-blies. The leading fuel cell type for automotive applications is the polymer electrolyte membrane fuel cell. FC buses, similar to battery electric vehicles, can potentially have a longer lifetime than conventional diesel buses.

The fuel cell converts chemical energy of hydrogen into electrical energy powering the engine. The general operating principle is functioning as follows: Hydrogen is fed into the fuel cell anode where it is split into protons (H+) and electrons (e-) by means of a catalyst. The membrane lets only protons (H+) pass, the electrons (e-) are forced to follow an external circuit, creating a flow of electricity. Oxygen is fed into the fuel cell at the cathode. Oxygen, electrons from the external circuit and protons combine to form water and heat. To achieve sufficient electrical power to propel a vehicle, multiple fuel cells have to be compiled into a fuel cell stack.

The current generation of FC buses has a hybrid powertrain architecture combining a fuel cell with a battery. In the first generations of FC buses, the fuel cell system directly powered the engine of the bus. The current generation of FC buses use batteries and in some cases supercapacitors for energy storage which improves energy efficiency. Fuel cell systems typically provide more than 100 kW power to the bus so that only smaller battery sizes are required (← 30 kWh). In some bus models, the integrated fuel cell system is used as a so-called 'range-extender' for the battery system which is then usually larger.

FC buses use hydrogen as fuel which is produced either by steam methane reforming or water electrolysis: Steam methane reforming is based on gas as feedstock (e.g. natural gas, methane gas, biogas, etc.) while water electrolysis uses electricity and water as feedstock. Hydrogen can be trucked in from centralized production plants of external suppliers or produced independently by the bus operator on the depot by electrolysis. Hydrogen is also produced as a by-product by the chemical industry, for example in chlorine production. Within the bus, hydrogen is normally stored in cylinders on the roof with a typical capacity of ~40 kg for a solo bus.

FC buses require dedicated infrastructure that is able to handle gaseous or liquid hydrogen for refueling. If hydrogen is produced off-site and trucked in over larger distances, liquefaction might become an economically viable option due to the lower required storage volume; usually, hydrogen is stored and dispensed in gaseous form. Hydrogen refueling stations (HRS) need to fulfill specific enhanced safety and permitting requirements as hydrogen is an explosive gas, especially if larger volumes are being handled. This can also make adjustments to other parts of bus depots necessary such as closed garages and maintenance facilities. So far, safety issues have not been a problem for bus operators running FC buses and related refueling infrastructure.

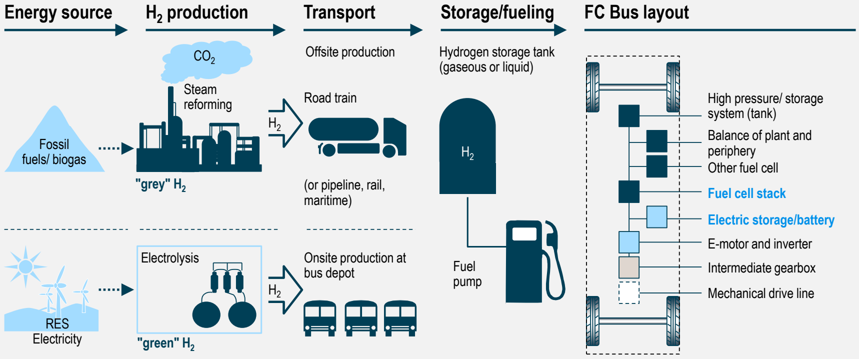

Figure 22: Hydrogen value chain and powertrain layout

3. Evaluation of renewable powertrain solutions for Ruter

This chapter includes an assessment of potential powertrain alternatives with regards to maturity, fuel and infrastructure availability, environmental, operational and economic performance. The chapter is based on recent reports as well as input from current European pilot trials of various bus powertrains and information provided by bus manufacturers, industry organizations, fuel and infrastructure suppliers and other sources. Some analysis is made specifically for Norway, Oslo and Akershus.

3.1 Introduction

Different powertrains have different benefits and drawbacks. Bus technology maturity, fuel and infrastructure availability and readiness, environmental performance as well as operational performance vary by technology. Diesel and biodiesel have very high maturity. Electric overnight charged buses, electric opportunity charged buses and fuel cell buses are maturing. For battery buses, a key challenge to be a key contender in the shorter term is the immaturity of batteries.

3.2 Bus technological maturity and commercial readiness

KEY MESSAGES

- Biodiesel and biogas powertrains are mature, with a high technical maturity, reliability and commercial readiness
- Powertrains running on bioethanol is a mature technology, but is currently limited to EURO V standard (EURO VI expected in 2017)
- PHEV parallel diesel could be fully commercially available in 2019 for 12 meter buses
- Battery electric and fuel cell buses are still immature and currently in test/pilot phase
    - 12 and 18 meter fully electric buses could be commercially available in 2017-2018 onwards, with 12 meter being more mature than 18m buses
    - Fuel cell buses are potentially alternatives in 2020 but provided by less OEMs than other battery electric buses

3.2.1 Current status and experience level of different powertrains

Figure 23 summarizes maturity levels in 2015 from a technical development perspective for different powertrain options. Our assessment of technical maturity is driven by a number of factors, including:

- Internal OEM testing
- Operating performance and functional experience from pilots/trials
- Key development needs
- Commercial availability

These factors combined represent and define the technology maturity level. In order for a powertrain solution to be considered highly mature, operational characteristics (such as reliability) should be in alignment with established technologies and the powertrain should be commercially available by bus manufacturers. Biodiesel is the most mature technology, leveraging the long history of traditional diesel buses.

Commercial readiness and availability, as a sub-component of technology maturity, is presented in chapter 3.2.2 and defined as:

- Serial production is ready and the technology is available "off-the-shelf" in larger quantities (c. 50-100 buses)
- Proper supply chain for spare parts and after sales services have been established

3.2.1.1 Biodiesel

Biodiesel is highly mature. Diesel buses that can run on B100 have high reliability and availability. However, there are certain operational problems with using FAME and RME-first generation biodiesel during cold winter days. Advanced second generation biodiesel however have winter capabilities similar to fossil diesel and function well in winter climate.

3.2.1.2 Bioethanol

High blends of bioethanol (E95, ED95) require both dedicated buses and infrastructure but low blends do not. There are certain buses manufactured for high blend (pure) bioethanol. The adaption of a conventional diesel bus to operate on bioethanol (ED95) was developed by Scania and first tested in Stockholm in 1986[48]. The technology is relatively mature with more than 1000 ethanol buses in operation in Europe, mainly in Sweden[49,50]. A four yearlong demonstration project called BEST, Bioethanol for Sustainable Transport, was conducted in several European regions and in Brazil between 2006-2009. The project was financed with support from the European Commission and coordinated by Stockholm city. Different technologies were demonstrated in the project in order to learn how public and private sector could create market conditions for a shift from fossil fueled vehicles to vehicles driven on renewable fuel. Within BEST, more than 150 ethanol buses were tested in 10 cities and regions. Scania today manufactures third generation ethanol engines that work in accordance with the diesel principle. Scania is the only vehicle manufacturer that produces bioethanol buses. The engines have similar energy efficiency levels as a standard diesel engine and currently fulfill the Euro V/Enhanced Environ-mental Vehicle (EEV) emission levels but not Euro VI. Thus, bioethanol can be said to have a high technical maturity but is commer-cially limited to EURO V.

3.2.1.3 Biogas buses

Biogas buses have high technical maturity. There are about 13 000 gas buses in the European Union countries[51], driven on biogas and/or natural gas. Natural gas is still the most commonly used gas but biogas demand is increasing, especially in Sweden. A CNG-bus engine can also be powered by biogas. Skånetrafiken is the public transport authority of Region Skåne in Sweden and the authority sees biogas as a significant part of their fossil free bus fleet for 2020. Currently Skånetrafiken has more than 700 biogas buses running[52].

3.2.1.4 Electric buses

There is no serial production targeting European or Nordic markets of fully electric buses today, but there is a continuous development of different electric bus technologies.

Fully electric buses are operating on a large scale (more than 1000 buses) in China (primarily overnight with large batteries) and also in South America (for example in Colombia). These buses are used in local markets significantly different to Ruter's situation, and often absence of e.g. EU/EC standards and Nordic packages for winter conditions. Some of the manufacturers have since adapted and certified their buses for European operations. Larger European operations do not yet exist, however several operational pilots with 1-3 buses are ongoing.

Currently, a number of pilots have been completed. Both fully electric overnight charged buses and opportunity charged buses are extensively being piloted. Figure 24 shows an indication of the number of bus trials in Europe by bus technology from 2010-2015 and announced going forward.

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[47] Source: Interviews and desk research - [48] Scania 2015 - [49] Bioethanol as sustainable bus transport fuel in Brazil and Europe
[50] Scania, 2015 - [51] Natural and Biogas Vehicle Association, 2015 - [52] Biogas buses – a cost estimate, 2012
[53] Source: Desk research, interviews

Powertrains		Technology maturity level 2015	Comments	Maturity Phase
Powertrains	Biodiesel	●	*Most mature technology, built on diesel power train*	*Commercial*
	Bioethanol	◕	*Relatively mature technology, built on regular ethanol techn., no Euro VI currently available*	*Commercial*
	Biogas	●	*Relatively mature technology, built on regular CNG techn.*	*Commercial*
	Electric - HEV	◕	*Parallel more mature than serial*	*Commercial*
	Electric - PHEV	◔	*Parallel more mature than serial*	*Technology testing / Pilots*
	Electric - overnight	◔	*Several pilots run*	*Technology testing / Pilots*
	Electric - opportunity	◔	*Several pilots run*	*Technology testing / Pilots*
	Electric – fuel cells	◔	*Several pilots run*	*Technology testing / Pilots*

● *High* ○ *Low*

Figure 23: Technological maturity overview 2015[47]

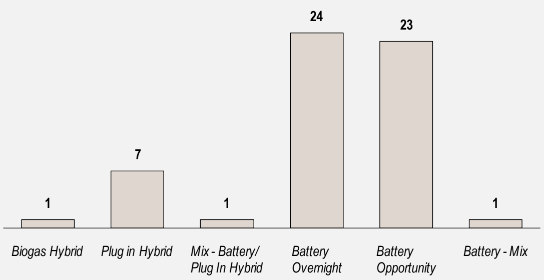

Figure 24: Number of trials in Europe by battery bus technology 2010-2015 and announced (both completed and publicly known plans),Non-exhaustive[53]

Electric – hybrids (HEV)

Among hybrids, standard diesel is the most common fuel to power the internal combustion engine even if biodiesel, bioethanol and biogas hybrids exist. Diesel-electric hybrids have been trialed and operated over more than a decade in some European countries. More than a 1,000 units have been reported to have been commissioned in Europe. A literature review suggests service uptime ranges from very high to 70-83% in Munich/MVG[54]. Moreover, biodiesel hybrid buses are commercially viable.

Biogas and bioethanol hybrids are less developed. There have been some trials, of which Stockholm tested 6 ethanol-hybrids with some 15% fuel savings achieved compared to a normal ethanol bus. There seems however be limited interest in the market for ethanol hybrids. Biogas hybrid buses are currently being tested by Skyss in Bergen with two 24-meter-long biogas hybrid buses purchased from Van Hool[55]. 15 similar buses are also tested in Malmö.

Electric – plug-in hybrids (PHEV)

Plug-in hybrids are a relatively new technology that is currently in operational test phases. Interviews and literature review suggest that plug-in hybrids are very attractive with high interest currently from operators, bus manufacturers and PTA (Public Transport Authority). A key benefit is that they can be run several kilometers in fully electric mode in certain zones, which is particularly attractive in urban or semi-urban routes.

It appears that parallel plug-in hybrids are more developed than serial ones. This can partly be explained by certain manufacturers' legacy to truck powertrain technologies. Interviews however mention that serial plug-in hybrids may be most suitable on routes where there is need for a high proportion of pure electric drive. On routes with steep slopes, parallel technology may be preferred for higher engine power.

Volvo appears to be one front-runner in the Nordics with involvement in a number of operational pilots with plug-in hybrid electric buses (Gothenburg and Stockholm). Västtrafik, the PTA in the Gothenburg area, piloted from the summer of 2013 until spring 2014 three plug-in biodiesel hybrids from Volvo. The project was fully financed by the European Union and the region VGR. Interviews with Västtrafik and its pilot suggest the bus solution using a pantograph (elevated from the bus) worked well after initial phase-in issues had been resolved. Initial issues also included cold batteries in the winter impacting battery performance (issue resolved by pre-heating), the charging arm of the infrastructure did not elevate properly, and the bus had problems with the door. With the plug-in technology, Volvo has been able to reduce both fuel consumption and emissions by up to 80% in the Gothenburg trial[56,57].

Battery capacity remains the key most important development area for plug-in hybrids and fully electric buses. For hybrids, it is however less critical as driving range is secured with the ICE. However, the desire to run on pure electric drive increases development needs of PHEVs. Please see discussion under full electric powertrains.

Fully electric buses

Fully electric powertrains have been and will continue to be tested in small scale operational pilots in a number of cities in Europe, see figure 25.

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[54] Clean Fleets, 2014 - [55] Skyss.no, 2015 - [56] Volvobuses.com, 2015 - [57] Interview with Västtrafik and Göteborgs Energi
[58] Source: Desk research, interviews - [59] Source: Desk research, interviews

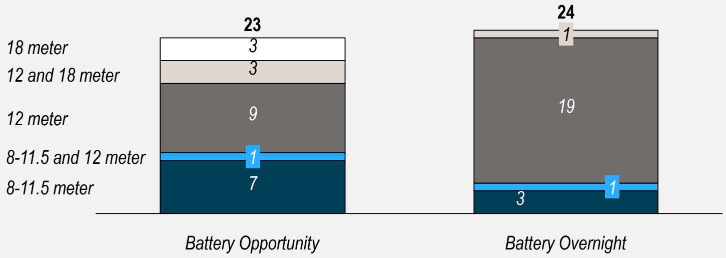

Figure 25: Overview of trials in Europe by bus length from 2010-2015 and announced (both completed and publicly known plans), Non-exhaustive[58]

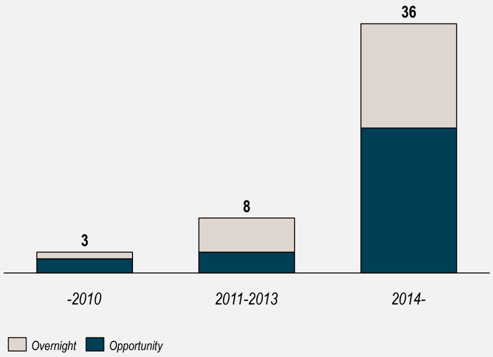

Figure 26: Overview of trials in Europe by start year, 2014- also includes announced trials (both completed and publicly known plans), Non-exhaustive[59]

Electric - Fuel cells

Fuel cell technology exists since several decades, whereas automotive applications have only evolved since the 1990s. The technology exists for a long period of time with a lot of operational experience collected without reaching its commercial breakthrough until now. In Europe major operational experience has been gained since the year 2000. About 83 fuel cell buses are in service at the moment in 16 different European locations, or about to start their operations to be part of normal public transport service in their respective areas of operation. Most important demonstration projects include:

→ **CUTE (Clean Urban Transport for Europe):** 9 European cities from 2001 to 2006 with 36 first generation fuel cell buses were operated in the first large-scale deployment project

→ **HyFLEET:CUTE** prolonged the operation of the buses used in CUTE from 2006 to 2009

→ **CHIC (Clean Hydrogen in European Cities)** is running from 2010 to 2016 with operation of 26 2nd generation fuel cell buses 5 European cities

→ **High VLO City, HyTransit and 3MOTION:** Additional demonstration projects are currently in preparation/ taking up operations in 7 additional European cities

→ **Individual projects:** A number of further cities have either tested fuel cell bus prototypes on a relatively limited scale or seen longer operations.

In total, fuel cell buses have been operated on more than 5.5 million kilometers in the last 10 years in Europe. Current ongoing trialing and demonstration activities aim at the further develop ment of the technology to facilitate its broad market introduction and commercialization. At the moment, fuel cell buses is still a maturing technology despite the large operational experience acquired; the powertrain architecture is complex and has until now reached availability levels of up to 80% only in the ongoing CHIC project with high variances, but below the project target of 85%. Even though significant improvements have been made in the last months of the project, limited vehicle availability and technology maturity remain major challenges for large-scale deployment of FC buses. So far, only very few bus OEMs have had fuel cell buses in their product portfolio, and even less have a product available today. The market for fuel cell buses is currently still quite immature and will need further significant development to reach commercial maturity.

As a conclusion, the degree of maturity varies among biofuel buses and electric buses. Electric buses are currently (2015) not sufficiently mature to operate as part of scheduled and regular bus traffic in Europe or in Oslo for Ruter.

3.2.1.5 Battery technology maturity and development

Battery electric buses were introduced more than a decade ago using changeable lead-acid batteries with a driving range of 50-60 km. These buses were usually small (approximately 10-15 passengers) and mainly used for very specific services and bus lines. However, with improving battery technology, driven by development for electric passenger cars, battery electric buses are becoming technically and commercially viable[60].

Maturity of battery technology is one of the two key drivers that have the strongest influence on the outlook of electric buses (the other is the infra-structure standardization and viability). When assessing batteries, there are two key parameters to consider. The first is price, which can be expressed in price per kWh and the other is performance, defined as kWh/kg, see figure 27.

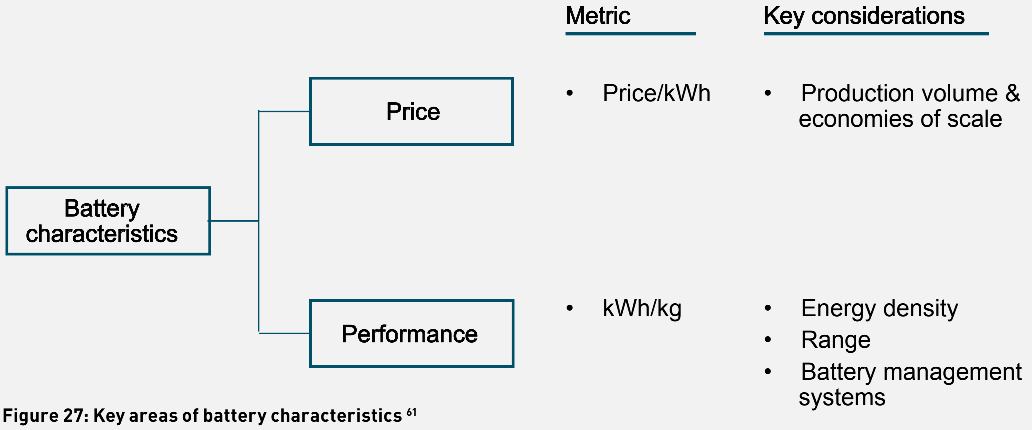

Figure 27: Key areas of battery characteristics [61]

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[60] VTT, 2012 - [61] Source: Interviews

Currently, batteries constitute about 25%-50% of the full electric bus purchase price depending bus type. Lower battery prices (price per kWh) are expected over the next ten years, see figure 28. Interviews suggest that batteries will mature and interviews indicate an annual price reduction (price per kWh) of c. 4-6% per annum towards 2020 and 2025. A key driver of falling prices is increasing production volumes. An interview with Utrecht and its electric bus pilot points out that investment in buses with smaller batteries could be considered more beneficial as battery prices declined quite a lot in the last years. The interview also points to that investments in large expensive batteries should be avoided[62].

According to interviews, battery technology performance (kWh per kg) is expected to improve marginally. Interviews suggest that up to c. 5% performance improvement could be expected annually until 2020. However, it is uncertain when new technology developments could be available for commercial buses. Historically, there have been performance improvements. For the future, views differ on when and how much battery improvement for commercial buses will improve. One bus producer reports that at the end of 2015, a second generation bus battery will be launched with 30% higher energy density compared to five years ago[64].

New technology might allow for higher density energy storage. Within the science and industrial community, new technologies are emerging (including nano-technology, new battery materials such as sulfur) potentially allowing for higher density energy storage. Interviews suggest this could allow for doubling the kWh/kg in comparison with the average today. However, the timing of this is very uncertain. Based on existing understanding, the view is that it is unlikely that this technology will materialize in serially produced buses until 2020. This report has not assessed the potential long-term impacts from emerging and radical developments.

Another potential area of performance improvement is expected to come from improved battery management systems, which can better control the battery and optimize cells and how the battery is used. Improved optimization of recharging cycles is also an important potential area of development.

Batteries are affected by cold climate. There are two key performance-related issues stemming from the impact of cold temperature (especially below minus 6 degrees Celsius according to interviews). The first is that batteries can malfunction if exposed to the cold and therefore the batteries are often protected in the bus chassis, in order to reduce the negative impact from the cold. The second issue is that the driving range is impacted. Interviews suggest that heating required for passenger comfort in the winter can increase energy consumption, possibly by up to 30% below certain temperatures. The common solution, to maintain battery power to drive the bus, is to use biofuel for heating the bus, and hence saving the electric battery for driving the wheels.

[62] Interview with trial in Utrecht - [63] Source: Industry interviews and information - [64] BYD, 2015 - [65] Interviews -
[66] Interviews, study analysis

Type	Est. share of bus purchase price 2015	Est. share of bus purchase price 2025
Opportunity	c. 25%	10-15%
Overnight (c. 320 kWh)	40-50%	20-30%

Figure 28: Battery share of bus purchase price and long-term outlook, excluding battery replacement [63]

LFP batteries are considered more safe (high electro chemistry stability even at high temperatures) and more environmentally friendly than LTO batteries.

Figure 29 summarizes the two key types of batteries used in electric buses, LFP and LTO. LFP is often used in overnight buses and LTO in opportunity charged buses[65].

In summary, the outlook points towards a price reduction of batteries, driven by economies of scale and increased demand for batteries. Performance may also improve from use of new materials and increase in energy density but there are significant uncertainties about the timing and level of improvement.

3.2.2 Commercial availability

Full commercial readiness of a bus technology is deemed important as evaluation criterion to reduce risks for Ruter as part of a larger implementation of new powertrain technologies.

Commercially ready is in this report defined as:

- Serial production is ready and the technology is available "off-the-shelf" in larger quantities (c. 50-100 buses)
- Proper supply chain for spare parts and after sales services have been established

The assessment of commercial readiness also needs to be understood by different bus lengths and classes (e.g. city, intercity).

There is a difference in commercial readiness across 12 meter, 13-15.5 meter and 18 meter buses. Typically, new technologies using 12 meter buses are most mature, followed by 18 meter buses. The 13-15.5 meter buses are generally the least developed.

Based on interviews and information from bus OEMs the bus producers' view of expected timing of full commercial readiness has been mapped. The information is based on the bus producers current product plans, and should be seen as the earliest point of time for when a larger order could be placed. The estimated timing should be viewed as an optimistic scenario as there could be delays. Small scale tests or pilots by Ruter could probably be conducted before the commercial readiness. The results on an aggregated level are described below.

Several powertrain technologies are available before 2020, however on different technology maturity levels. In general, 12 meter electric buses have earlier commercial readiness than 18 and 13-15.5 buses. Even if several OEMs are providing a powertrain solution, there might still be different risk levels compared to fully mature technologies. For example, there might be variations with regards to sufficiently testing in winter conditions and other operating characteristic facing Ruter, such as topography, range, and reliability, might still differ even if several OEMs provides the powertrain. Only one OEM providing the powertrain is potentially more risky and potentially not a realistic option for Ruter.

Battery type	Energy density [kWh/kg]	Charge cycles	Life expectancy	Typical price index	Annual performance improv.	Annual price improvement	Reduced environmental impact
Lithium Iron Phosphate (LFP, LiFePO4)	●	◐	◕	Index 100	c.5%	c.5%	●
Lithium Titanate (LTO)	◔	●	●	Index 200	c.5%	c.5%	◐

● *High* ○ *Low*

Figure 29: Overview, LFP and LTO batteries[66]

Biodiesel and biogas buses are well established and the commercial option with the highest commercial availability. Hybrids are currently offered by a limited number of OEMs as the technology is still maturing and Biodiesel parallel PHEVs are expected to be fully commercially ready from 2019. Biogas HEVs and PHEVs are not estimated to be commercially available before 2022-2023. Parallel drivetrains are more mature than serial hybrids. This can be because parallel hybrids have been developed for commercial trucks and technologies and costs are shared. Within fully electric vehicles, both 12 meter overnight and opportunity charged buses are estimated to be fully commercially available from 2017 (overnight buses today are mainly from non-European OEMs and have not been tested fully in Nordic climate and required aftermarket service is not yet in place). In addition, there are risks related to lack of infrastructure standards, implying investment now could create lock-ins to an infrastructure that may not be standard in the future (see later discussions).

Commercial readiness of 18 meter buses is behind that of the 12 meter buses. Today, 18 meter buses are mainly powered by biofuels. 18 meter parallel HEVs are available from individual OEMs and by more OEMs in 2020-2021, then with biodiesel as the fuel. 18 meter fully electric buses, both overnight and opportunity charged, have the earliest commercial readiness in 2017. Overnight charged buses are behind 12 meter as the inherent limitations of large batteries with respect to route range are even more an issue for 18 meter buses. Although fully electric buses are stated by OEMs to be relatively mature by 2017, these buses still today have limited Nordic operational experience. As to 18 meter fuel cell buses, there seems to be limited plans to develop articulated fuel cell buses; therefore it is currently uncertain if fuel cell 18 meter buses will become an option for Ruter.

13-15.5 meter buses have lower commercial readiness compared to 12 and 18 meter buses. Biodiesel is currently the most available technology, followed by biogas. There seems to be few plans to bring serial hybrids, overnight charged buses or opportunity charged buses of this length to the market before after 2020. Similarly, there will be few fuel cell buses models too. 13-15.5 meter buses using new technologies are believed to have a high availability of Class 2 buses (bus mainly equipped with seats and often targeted regional areas).

Further, from the sample of OEMs, smaller opportunity fully electric buses (8-11.5m) will be available by only a very few producers until after 2017. Outside the current sample of OEMs and with a different geographical focus, there are certain manufacturers that have smaller buses running in pilots or even as part of the regular service. The potential fit to operations in Oslo region has not been assessed.

There are few examples of electric buses operated on own commercial merits in Europe. When assessing commercial maturity developments and drawing conclusions from pilots, it is important to keep in mind that a high share of pilots have been funded by the public. In the European Union countries, full or partial grants from the EU seem to be the funding source for most pilots. Other contributors to pilots appear to be the counties and municipalities in the respective region. Sometimes the national energy authorities also provide partial funding. To date, there is no or few examples where electric standard solo buses are operated on own commercial merits. Interviews suggest this could change and that from 2015, first orders of pilots are being placed without grants.

3.2.2.1 Bus manufacturers

When considering powertrain technologies and commercial maturity, it is important to understand the context of OEMs. These have varying backgrounds - geographically, technically, economically, and different presence and experience in environments similar to Ruter's. There can also be differences in quality and the adaptability to the Norwegian market and customer requirements.

Not all powertrain models are offered by all OEMs, as they have different powertrain strategies and have to prioritize R&D resources. For example, certain manufacturers have chosen to stop developing traditional ICEs and solely work with HEVs and other electrified powertrains. Others have decided not to develop biogas solutions and almost all OEMs in the sample do not seem to focus on bioethanol[71].

Regarding focus of battery electric buses, bus manufacturers can be divided into a number of groups, with different legacies, strategies and strengths and weaknesses. The focus of electric buses and current state of development differs. In figure 34, there is a schematic of different types of bus manufacturers. The bus market today for city

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[71] Source: Interviews with bus OEMs -[72] Source: Interviews with bus OEMs

buses is dominated in volume terms by the traditional bus manufacturers. These often have a legacy and relation with commercial trucks. As to full electric offerings of these manufacturers, they appear to focus on plug-in hybrids in the shorter term, with full electric buses being commercially ready later compared to for example niche bus manufacturers or manufacturers with a legacy in battery development.

In general, buses designed and produced for non-European markets can normally be homologated to European standards. However, according to interviews, certain trials with overseas produced buses have encountered homologation problems and never reached final approval.

Type	Origin	Legacy	Battery electric offering maturity
Traditional bus manufacturer	Europe	Power train specialist. Complete bus focus	**Technical testing.** Some variations depending on powertrain strategies chosen. Focus currently on electric hybrids
Bodybuilders	Europe	Develop commercial product	**Operational pilots.** Can pick and choose from chassis
Niche bus manufacturer	Europe	Abandoned traditional PTs and refocused to innovative PTs and energy solution	**Operational pilots.** Question about ability to industrialize and deliver larger volumes
Battery manufacturer	China	Battery technology	**Operational pilots.** Adaptability, quality for Norway

Figure 34: Overview of types of electric bus manufacturers supplying Europe today and degree of current maturity[72]

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[72] Source: Interviews with bus OEMs

3.3 Fuel and infrastructure availability

KEY MESSAGES

- The availability of environmentally friendly electricity (green energy) and biogas (based on sewage and waste) is high in Oslo
- The availability of high quality HVO-biodiesel and bioethanol is also estimated to be high in the near future, although for a limited number of buses. Biodiesel suppliers indicate medium availability but bus manufacturers are more restrictive regarding availability
- Oslo region has current biogas availability for c. 380 buses, however maximum production capacity is higher
- Infrastructure standardization for electric charging infrastructure is still in the development phase
- Standardization of charging infrastructure in communication protocols is closest for pantograph solutions
- DC charging appears to have more benefits than AC charging (less equipment on bus, depot power optimization)

As different powertrain solutions vary in maturity, there are also variations in fuel and infrastructure availability and maturity. The analysis of fuel availability takes into consideration the supply and demand of a fuel in general and the availability in Oslo in particular. The availability of high quality renewable fuel is evaluated by supplier capacities as well as number of suppliers providing the fuel.

3.3.1 Fuel availability

Regarding fuel availability, the aim should be to have high availability of renewable fuel with low CO2-impact when analyzed well-to-wheel.

3.3.1.1 Biodiesel - Potential to supply from broader Europe

Biodiesel availability in Europe is high, although there are high variations in quality. The EU is the world's largest biodiesel producer and biodiesel is considered by many the most important biofuel in the EU. With regards to energy, biodiesel represents approximately 80 percent of the total transport biofuels market in the EU[73]. Specific production and consumption data for European biodiesel is presented in figure 35.

The EU biodiesel production is driven by domestic consumption and competition from imports. As seen in the figures, the biodiesel consumption is higher than the production within the European Union, due to import. This does not mean that the availability of biodiesel is low in Europe; there is capacity surplus in the refineries in Europe (average capacity use in 2015 forecasted to 42%).

The quality of the European biodiesel, especially with regards to CO2-footprint, varies. An overview of the feedstock used for biodiesel in Europe is presented in figure 36.

More than half of all biodiesel consumed in Europe 2013 was made from rapeseed[76] which is not preferred from an environmental point of view, see next chapter. Because of environmental concerns, there is an increased production and availability of advanced biofuels within Europe, such as HVO. In Benelux and Finland alone, 1,240 million liters HVO (11.4%) were produced in 2014[77].

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[73] U.S. Department of Agriculture (USDA), 2014 - [74] Source: U.S. Department of Agriculture (USDA), 2014
[75] U.S. Department of Agriculture (USDA), 2014, Global Trade Atlas, European Biodiesel Board (EBB), Eurostat, Roland Berger

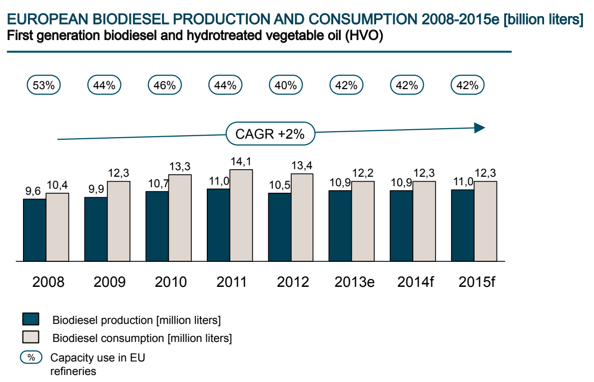


Figure 35: European biodiesel production and consumption[74]

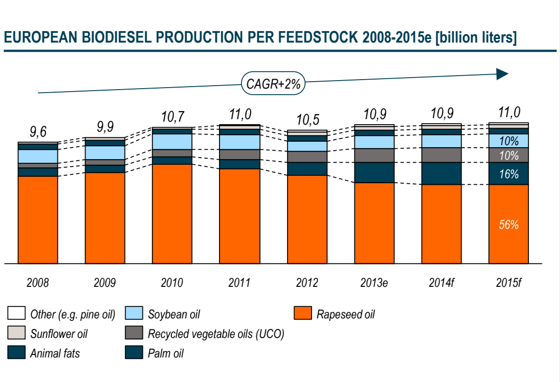
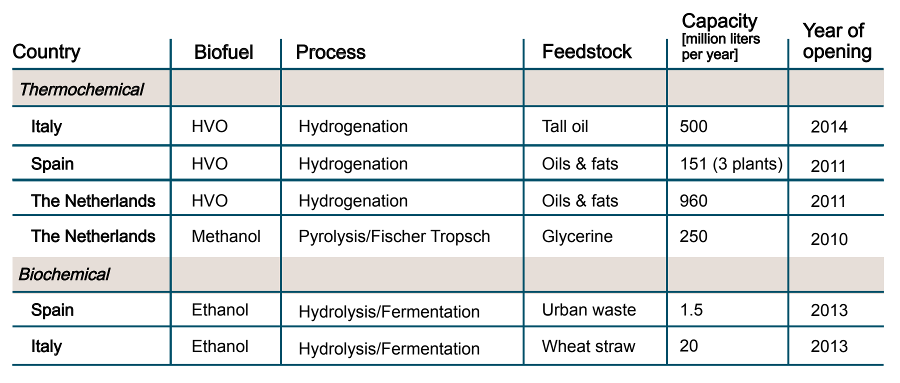
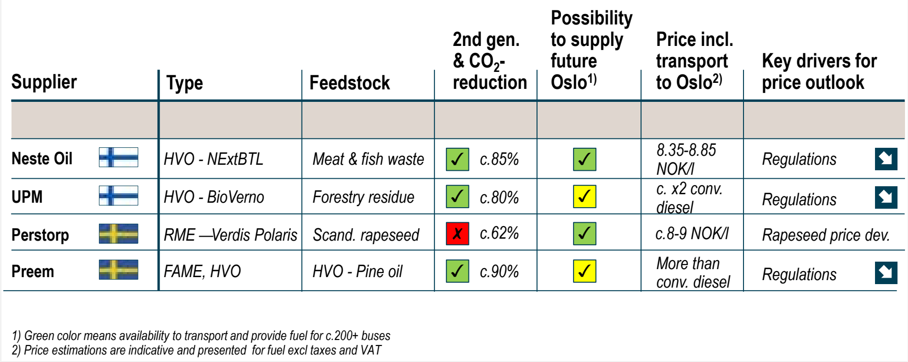


Figure 36: European biodiesel production per feedstock[75]



Country	Biofuel	Process	Feedstock	Capacity [million liters per year]	Year of opening
Thermochemical					
Italy	HVO	Hydrogenation	Tall oil	500	2014
Spain	HVO	Hydrogenation	Oils & fats	151 (3 plants)	2011
The Netherlands	HVO	Hydrogenation	Oils & fats	960	2011
The Netherlands	Methanol	Pyrolysis/Fischer Tropsch	Glycerine	250	2010
Biochemical					
Spain	Ethanol	Hydrolysis/Fermentation	Urban waste	1.5	2013
Italy	Ethanol	Hydrolysis/Fermentation	Wheat straw	20	2013

Figure 37: 2nd generation biofuels in EU [78]



Supplier	Type	Feedstock	2nd gen. & CO_2-reduction	Possibility to supply future Oslo¹⁾	Price incl. transport to Oslo²⁾	Key drivers for price outlook
Neste Oil	*HVO - NExtBTL*	*Meat & fish waste*	✓ *c.85%*	✓	*8.35-8.85 NOK/l*	*Regulations* ↘
UPM	*HVO - BioVerno*	*Forestry residue*	✓ *c.80%*	✓	*c. x2 conv. diesel*	*Regulations* ↘
Perstorp	*RME —Verdis Polaris*	*Scand. rapeseed*	✗ *c.62%*	✓	*c.8-9 NOK/l*	*Rapeseed price dev.*
Preem	*FAME, HVO*	*HVO - Pine oil*	✓ *c.90%*	✓	*More than conv. diesel*	*Regulations* ↘

1) Green color means availability to transport and provide fuel for c.200+ buses
2) Price estimations are indicative and presented for fuel excl taxes and VAT

Figure 38: Selected biodiesel suppliers in Nordics [79]

Both Finland and Sweden have production of high quality HVO-biodiesel, presented in next chapter. Selected 2nd generation suppliers in Europe are presented in figure 37.

3.3.1.2 Biodiesel - Availability and capacity in Nordic region

First generation rapeseed-based biodiesel (imported from Denmark) is the most commonly used biodiesel in Norway. However, there are potential suppliers of 2nd generation biodiesel to Oslo, see figure 38.

High quality HVO is produced by Neste Oil in Finland. Neste Oil produces around 0.34 million tons per year renewable diesel (NExBTL) in a refinery in Porvoo, Finland. Neste Oil also has a second refinery in Finland and two more in other European countries. Initially 90 % palm oil was used as feedstock but this has now been reduced to 40%. In the Finnish refineries, 60% is made of slaughterhouse and fish waste. Palm oil is not used at all in the Finnish refineries. The goal for 2017 is to have 100% waste base as feedstock. Other feedstock used are waste oils such as frying oil, animal and fish fat, camelina, soy and rapeseed oil. NExBTL from Finland has a CO2-reduction of 85% compared to conventional diesel (including 300 km in transport) and no fossil fuels are used in the production. Neste Oil has done both summer and winter tests and the HVO functions trouble free in winter climate. The price of NExBTL is about the same as for fossil diesel including taxes and the fuel will be available for transport to Oslo. The supplier of NExBTL in Norway, ECO-1, gives a price indication of 8.25-8.75 NOK per liter excluding taxes and 0.10 NOK per liter for transport to Oslo[80].

High quality HVO is produced by UPM in Finland. Another producer of biodiesel in Finland is the Finnish pulp, paper and timber manufacturer UPM, UPM-Kymmene Corporation. UPM has the world's first wood-based renewable diesel biorefinery in Lappeenranta, producing wood-based renewable diesel from forestry residue (tall oil) called UPM BioVerno diesel. The production started in January 2015 and has an annual renewable diesel production of 100 000 tons or 120 million liters (equivalent to approximately 6000 buses with 40000 km/year and consumption 0,5 l/km). Production at the UPM Lappeenranta Biorefinery will provide about 25% of Finland's biofuel target

[78] Source: U.S. Department of Agriculture (USDA), 2014 - [79] Source: Study results, interviews - [80] Interview with Neste Oil and Eco-1, 2015

for transport use according to UPM. Further, according to the company, the BioVerno diesel works well during winter time and works with all diesel engines, just as conventional diesel. The fuel has a CO2-reduction of about 80% compared to conventional diesel even though natural gas is used in the production. The availability in Oslo is according to UPM limited since Finland will be using the majority of the supply. However, there are no certain regulations regarding the supply and UPM is open for discussing export in the future as well. The price is high, almost twice the price of fossil diesel[81].

RME-based biodiesel is produced by Perstorp in Sweden. Perstorp in Sweden provides a biodiesel named Verdis Polaris. The biodiesel is RME-based and the feedstock used is Scandinavian rapeseed and therefore the biodiesel is considered first generation. The capacity is 135 000 tonnes per year. The fuel functions well in winter climates but below -15 degrees Celsius, blending with fossil fuel might be necessary. Verdis Polaris offers a CO2-reduction of about 58-62,6% and fossil methanol is normally used in the production of RME-based biodiesel. Perstorp however offers use of a renewable methanol in the production if the customers require it, to a premium price. For the buyer it is not possible to verify that the renewable biodiesel bought is actually fossil free but the producer issues a certificate. The production is based in Stenungsund in Sweden, 250 km from Oslo and there is capacity to provide fuel for more than 200 buses in Oslo. The price is 8.3 SEK/liter + 0.25 SEK/liter for transport to Oslo[82].

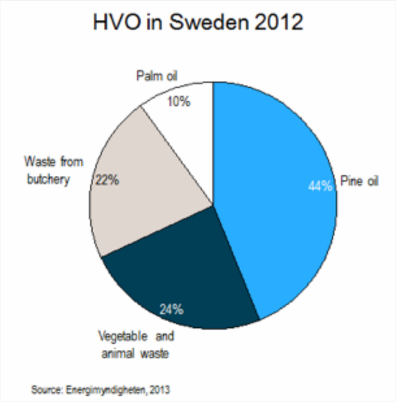
Preem is the only HVO-supplier in Sweden. Preem in Sweden produces both RME and HVO-based biodiesel and is the only HVO-supplier in Sweden. In interviews with Preem they point out that if HVO is to be used in a diesel engine, clarification and clearance from the bus manufacturer are needed. Not all biofuels meet the EU requirement for standard diesel fuel (EN 590 standard) and verification by the bus manufacturer is recommended before fueling a bus with new biofuel. The Preem RME includes 5.3% methanol which is produced by natural gas and therefore not fossil free. The pure HVO however, made from crude tall oil is 100 % renewable and also functions well in winter climate. The HVO has a CO2-reduction of about 90% and is more expensive than fossil based diesel. Regarding the price development, Preem points to regulations as the main driver of price changes. The Preem HVO is not used today in its pure form and therefore the supply capacity for pure HVO from Preem to Oslo is relatively limited. There will be increased availability in the future according to Preem[83].

There are two Norwegian industrial initiatives for biofuels today: Statkraft and Södra in Tofte in Hurum and Viken Skog/Treklyngen in Follum, Hønefoss. Both projects are looking at the opportunities to produce biodiesel for heavy transport needs and bio-jet fuel for aviation needs. Statkraft and Södra have in Norway established a company for future production of second generation biofuels. The company is called Silva Green Fuel As and forestry and wood will be the feedstock for the fuel[84].

Viken Skog and Avinor are working with establishing a factory for production of biofuels for the aviation industry, so called Jet A-1, at the site of the old Follum factories outside Hønefoss. In 2013, Avinor entered an agreement with Viken Skog to support an innovation center that investigates the possibility of biofuel production for aviation needs based on Norwegian forestry feedstock. Biofuel for road transport will be a byproduct from this production process.

Suppliers of biodiesel are in general optimistic regarding the availability of high quality second generation biodiesel, although the availability is not unlimited. Bus manufacturers are more restrictive and indicate that the availability might not be as high as indicated by suppliers[85].

In Sweden, the use of biofuels increases. Between 2011 and 2012, the usage of biofuels increased with 17%[86] and now has an 8.1 % share of the road traffic in Sweden. Biodiesel is the biofuel with highest increase and now represents more than half of Sweden's biofuel-usage. Bioethanol stands for 35% and biogas for 12%. With regards to biodiesel, pine oil is the most commonly used feedstock for HVO[87] in Sweden, see figure 39 below.



Source: Energimyndigheten, 2013

Figure 39: HVO biofuel in Sweden 2012[88]

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[81] Interview with UPM, 2015 - [82]Interview with Perstorp, 2015 - [83]Interview with Preem, 2015 [84]http://www.statkraft.no/media/pressemeldinger/2015/statkraft-og-sodra-oppretter-biodrivstoffselskap - [85]Interviews- [86]Energiläget, 2013 - [87]Energimyndigheten, 2013

Regulations are the main price driver for biodiesel, according to interviews. Taxes and fee levels highly affect the supply and demand for a certain biofuel. The second most important driver for price development is the oil price development. Oil forecasts vary and the predictability of future prices is considered low[89].

3.3.1.3 Bioethanol - Potential to supply from broader Europe and Brazil

There is a global supply of bioethanol, especially sugar-based bioethanol from Brazil. However, the sugar-based fuel is a first generation biofuel and the CO2-reduction is lower compared with forestry feedstock used in Scandinavia. The bioethanol consumption in Europe is increasing at a pace of approximately 7% per year, see figure 40.

The European consumption of bioethanol is higher than the production but the factories still have free capacity in general (63% capacity use forecast for 2015). The gap is due to import of bioethanol, mainly from Brazil.

3.3.1.4 Bioethanol - Availability and capacity in Norway 2015

The availability of ED95 in Norway is limited. In 2013, there were filling stations in Oslo, Bergen, Trondheim and Vestby[91]. However, it is also possible to order ED95 directly to depots and there are suppliers of bioethanol both in Norway and Sweden offering this possibility. Currently Ruter has c. 20 buses running on bioethanol that is made from wood/forestry feedstock from a Norwegian factory in Borregaard[92]. The factory uses clean electricity from waterpower in the factory and therefore the production and fuel are fossil free with the exception of fossil content in the ignition amplifier used in the bioethanol (additive in the last percent of the ED95). The additive is made in Sweden by Akzo Nobel or SEKAB. The feedstock used is Swedish and Norwegian spruce and the CO2-reduction is about 80-85%. However, Borregaard are currently working on a life-cycle analysis and there are some uncertainties regarding if fossil components in the additive is considered or not.

The operational performance is considered high according to Borregaard and there are no problems using the fuel all year around. The capacity in the factory is about 20 million liters per year and the availability for buses in Oslo is high. The price is about 8-9 NOK/liter and the price is relatively stable according to Borregaard[93], see figure 41.

Another supplier of ED95- bioethanol is Sekab in Sweden. Sekab used various feedstock and buys for example Europe-ethanol (66% CO2-reduction), sugar cane from Brazil (71% CO2-reduction) and also forestry based 2nd generation (87% CO2-reduction). It is possible to order solely 2nd generation bioethanol from Sekab. The price for this forestry-based ED95-fuel is about 8-9 NOK/liter including transport to depot in Oslo and there are no supply issues to Oslo according to Sekab[94].

3.3.1.5 Biogas - Potential to supply from broader Europe

The growth in biogas as a fuel tends to be greater in geographies with an extensive national gas grid and a current market for Compressed Natural Gas vehicles. Sweden, The Netherlands, Germany and Austria are examples of countries leading the development of biogas investments. Sweden's development is driven by public transport initiatives, as well as fuel tax exemptions (which is also the case in Germany)[95]. In 2013, there were over 14,500 biogas plants in Europe with an installed capacity of 7,857 MW[96].

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[88] Source: Energimyndigheten, 2013 - [89] Source: Wall Street Journal\Haver Analytics, average price estimations from 47 banks, 2015
[90] Source: U.S. Department of Agriculture (USDA), 2014 - [91] Sør-Trøndelag Fylkeskommune, 2014
[92] http://www.borregaard.com/News/Bioethanol-from-Borregaard-in-petrol - [93] Interview with Borregaard, 2015
[94] Interview with Sekab, 2015 - [95] Clean Fleets, 2014 - [96] EBA, 2014

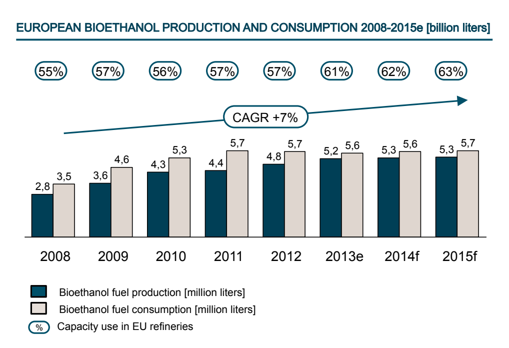
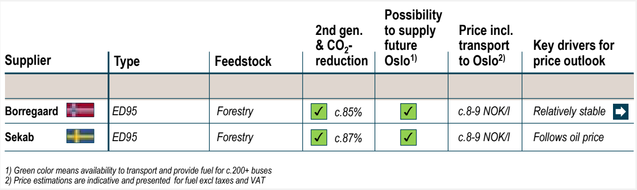


Figure 40: European bioethanol production and consumption [90]



Supplier	Type	Feedstock	2nd gen. & CO_2-reduction	Possibility to supply future Oslo[1)]	Price incl. transport to Oslo[2)]	Key drivers for price outlook
Borregaard	ED95	Forestry	✓ c.85%	✓	c.8-9 NOK/l	Relatively stable ➡
Sekab	ED95	Forestry	✓ c.87%	✓	c.8-9 NOK/l	Follows oil price

1) Green color means availability to transport and provide fuel for c.200+ buses
2) Price estimations are indicative and presented for fuel excl taxes and VAT

Figure 41: Selected bioethanol suppliers in the Nordics

3.3.1.6 Biogas - Availability and capacity in Norway 2015

High quality biogas is available in Norway and therefore imports of European production are of less interest. Figure 42 below shows that the theoretical energy potential of biogas resources from waste/by-products in Norway is estimated to be nearly 6 TWh/year. If the potential of available forestry resources of approximately 20 TWh should be taken into consideration, the potential is almost 26 TWh/year.

Although there is a high theoretical potential, availability in reality is much lower. In the central eastern part of Norway, there is an estimated availability of 7600 TNm3 per year which equals fuel for approximately 380 buses. However, the maximum biogas production potential is higher, c. 27000 TNm3. In East and Southern Norway, the estimated availability of biogas produced by several producers is estimated to 16100 TNm3 or fuel for approximately 805 buses (maximum biogas production potential c. 48000 TNm3).

3.3.1.7 Electricity - Availability and capacity in Norway 2015

Norway in general and Oslo in particular have high availability of green electricity and therefore good conditions for using electric buses. However, the high peak loads on the electricity grid during the short time caused by the charging might be challenging. If electricity certificates are bought, the electricity is to be considered renewable.

About 6 of the 23 depots used today seem to offer the power requirements of 50-125 kW required for charging. About 200 buses operate from these 6 depots. Two additional depots have grid capacity but lack double sided supply. This means that a high share of both the other depots and buses used in Ruter's area will need infrastructureinvestments if large scale electric charging should be deployed.

3.3.1.8 Hydrogen - Availability and capacity in Norway 2015

Hydrogen can be produced from various sources with the potential for nearly unlimited supply by independent on-site production at bus depots by electrolysis. The main fossil free sourcing options for hydrogen include:

- **Sourcing of H2 as industry by-product:** Hydrogen is a frequent by-product from the chemical industry, notably from chlorine production by electrolysis. Although this in many cases is the most cost-efficient hydrogen source, production processes need to be analyzed in detail to assess their environmental impacts and ensure that Ruter's sustainability criteria are met. In addition, the opportunity to source H2 as an industry by-product requires the existence of relevant chemical industry in the region and the readiness of concerned companies to start treating H2 for provision as a fuel which is currently mostly being vented.
- **Production by electrolysis** using water and electricity as feedstock: Production by electrolysis can be realized either by a centralized production facility run by an external supplier or by decentralized production directly at the bus depot, as currently done at Ruter's Rosenholm bus depot at the refueling station operated by Air Liquide. If electricity produced from renewable sources is used, nearly unlimited supply can be guaranteed independent of external suppliers.
- **Production from steam methane reforming** using biogas as a feedstock: Can either be done in centralized large production facilities of external suppliers with delivery to the bus depot or in decentralized production facilities directly at the bus depot. Due to more economic usage of biogas directly buses without converting it into another type of fuel, this type of hydrogen production is less relevant – at least as long biogas buses are in operation

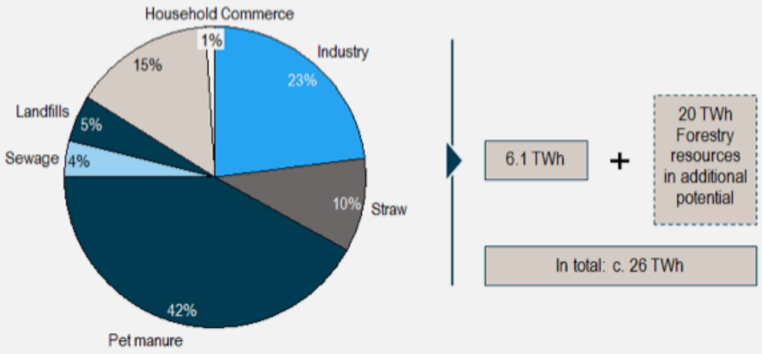


Figure 42: Biogas potential in Norway[97]

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[97] Sør-Trøndelag Fylkeskommune, 2014

In Norway, several actors are actively engaged in establishing a sustainable hydrogen supply chain. There are high ambitions to develop hydrogen as a fuel in the country and deploy a corresponding HRS network and production capacities. Until now achievements have been limited and no large scale production facilities for hydrogen exist as an external supply source for Ruter.

Hydrogen production from electrolysis offers nearly unlimited fuel availability to Ruter, but requires significant investment. Own fuel production normally is not part of the scope of activities of bus operators or public transport authorities and not a feasible option for most renewable fuels. In the case of hydrogen, this option is available and has the advantage for Ruter to be independent of external suppliers – at the same time, required electrolysers are a heavy additional investment and need significant additional space at bus depots. As specific expertise is required to operate and maintain such production facilities, involvement of specialized external service providers is normally necessary. As H2 production from electrolysis is considered the most sustainable option by relevant players in Norway and the market is still in an early development phase, on-site H2 production from electrolysis will be the primary H2 source for Ruter at least in the mid-term.

3.3.2 Infrastructure solution availability

Below infrastructure solutions availability are presented for different fuels. Infrastructure is evaluated by technological maturity and existing installations in Oslo and the reliability of infrastructure solutions.

3.3.2.1 Technological maturity and existing installations in Oslo

Biofuel infrastructure has high technical maturity and is already installed in Oslo. Biodiesel, biogas and bioethanol infrastructure is basically the same as being used for conventional diesel or CNG buses which is commercially available in the market and is in widespread daily operational use. The respective solutions have high technical maturity and are already installed and used in bus operations in Oslo. Biogas infrastructure is typically more complex as handling a gaseous fuel, but is also technologically mature and used with extensive operational experience. Required refueling times are typically very short, thereby not interfering with operational schedules. For biogas, slow fuelling also is an option if this method fits to operational planning.

Electric charging infrastructure is not mature today and charging standards are lacking. From a technology development point of view, depot charging systems are overall seen as simple and similar applications are also being used in the automotive industry, which leads to an overall more advanced state than for opportunity charging systems. The systems used today are often simple AC charging systems, which provide grid electricity at required voltage levels to the bus whereas the conversion from AC to DC power is done by an on-board conversions unit. AC charging is typically using standard 3-phase AC cables and plugs that are manually connected to the bus. It is simple, inexpensive, and easy to implement. These plugs are commonly used, however, different standards exist. These depot plug solutions have several disadvantages:

- Charging speed is limited as only limited power output can be provided to the bus
- AC depot charging requires high redundancy in grid power
- In addition, on-board chargers add weight to the bus and are a costly component with a limited number of suppliers

An alternative for AC depot charging is systems providing DC power output to the bus, which alleviates the disadvantages of the AC charging systems, but typically adds costs for installation of such systems. On the other hand, DC charging systems allow for improved power control and balancing of peak electricity demands at depots. Both types of systems are normally scalable by either increasing output power of individual chargers (with limitations for AC chargers though) or simply adding more chargers or modules to the system at an individual depot. Both ways imply higher electricity supply needs from the grid so that an upgrade of existing grid connections or installation of larger transformers might be required.

For opportunity charging, both inductive and conductive opportunity charging systems lack significant operational experience today. Both types of systems have been installed in a number of trials so far with perceived acceptable results. Early implementation issues for both kinds of infrastructure have been detected. Currently, ultra-fast charging solutions are under development and offered by several suppliers whereas operational experience with such systems is even more limited. Currently, limitations to such systems are not so much set by the infrastructure side as by available battery technologies, which are either not able to take such high amounts of charging power or are being degraded much quicker when being exposed to ultra-fast charging. The quality of batteries is also important, and there are differences in quality between producers, implying potential restrictions on what Ruter can allow. Opportunity charging solutions are typically also scalable in the sense of adding additional charging power to a once installed system; as a consequence, upgrades of grid connections might also be needed.

Inductive opportunity charging solutions offer several advantages and disadvantages – conductive seems preferred by majority of industry at least medium term: Inductive charging systems are installed underground, thereby being less visible. Less building impact could be particularly beneficial in historical areas or other areas where building restrictions may be high. Other benefits is that the inductive charging plate has no mechanical parts, which will not be impacted by wind, violence etc. Inductive charging has limited or no operational pilots in climatic situations similar to Oslo. There are reports that there is sensitivity that the bus and the charging inductive plate needs to be aligned horizontally and vertically (tolerance zone). If there is snow impacting the distance between the bus and the plate, this would result in higher power losses. Industry interviews suggest that efficiency is about 90% or higher, meaning the power loss is about 5-10%. The cooling unit is part of the energy loss. Inductive charging is currently restricted to 200 kW charging into the battery[98]. Table 43 outlines some of the pros and cons with inductive charging vs. conductive. Overall, it seems that conductive is more accepted by the bus manufacturers and operators interviewed. See figure 43 below for comparison between conductive and inductive charging.

As of today, the first installation of inductive charging in Nordic climate is planned by Scania to run in Mälardalen in 2016. This is initially a technology test (static charging stand at Scania's facilities in Södertälje). In a second step, the charging installation will be moved to another part of Södertälje. Trials in Braunschweig, Utrecht, Genoa, Torino and Milton Keynes are currently using inductive charging systems. Berlin und London will start operating tests in 2015[100]. As of now, Bombardier and its Primove inductive charging system appear to be the most known inductive system. There are also other manufacturers of inductive charging, which have provided inductive charging systems to New Zealand, Turin, Genoa, Milton Keynes and Umeå[101].

Pantograph charging solutions have a long track record in transport applications, while stationary charging points are only coming into service today. Pantographs are widely used for trains, trams and trolley buses, but in these applications pantographs usually have a constant connection to the overhead wire. For stationary charging for electric buses, opportunity charging points are being installed which either have the pantograph on the charging mast which connects the mast and bus (also called inverted pantograph solution), or have the pantograph installed on the bus which connects to the recharging mast once it its reached (conventional pantograph). Pantograph solutions can also cater for high power/fast charging capabilities (e.g. 300-650 kW)[102]. There are at least three providers of conductive pantograph bus charging solutions today: ABB, Siemens, and Opbrid[103]. As it seems today, inverted pantograph solutions are expected to emerge as the future standard for such charging solutions as reduce the weight if vehicles as well as the total number of pantographs to be installed (one per mast used for several buses vs. one per bus). Current trials with pantograph charging solutions include Hamburg, Dresden, Geneva, Stockholm, Umea;

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[98] Bombardier, 2015 - [99] Source: Industry interviews

	Conductive	Inductive
Energy efficiency	95+%	90+%
300+ kW charging	Yes	No
Off-board infrastructure costs	Medium	High
Onboard weight of components	Low	Medium
Tested in Nordics	Yes	No
Communication protocol standard	Maturing	Immature
Perceived industry preference currently (from interviews)	Yes	No

Figure 43: Summary of inductive versus conductive charging[99]

future installation is planned in Cologne and Gothenburg amongst others.

Currently, efforts are being undertaken to standardize charging infrastructure. This process is mainly being driven by UITP and IEC aiming at introducing a common standard for plug-in charging systems. There is some probability that DC charging will be the preferred solution in the future for which CCS is likely to become the commonly accepted standard for plugs. For pantograph conductive charging solutions different types of pantographs are still being used. It is expected that standardization is also taking place within the next years, but discussions are not as advanced as for plug-in connections. Most infrastructure and bus suppliers currently offer to integrate any kind of charging connection standard to be installed in their products, reflecting on the one hand the lack of available standardization, while on the other hand catering the need of bus operators to be able to use the same infrastructure installed for different kinds of buses from different manufacturers. Standardization of communication protocols used by the charging infrastructure is another key area of future development required in terms of standardization. More specifically, the communication between the bus and the charging infrastructure is where development is needed. Communication is to ensure that right power is loaded into the bus, where the bus' battery management system plays an important part. There are ISO standards (e.g. ISO 15118) developed of bus electric vehicle applications. For pantograph charging, and overnight charging using Combo-2, communication protocols appears more developed. For inductive charging, no standards are yet developed, and interviews suggest this will probably not happen before 2020[104]. It is important that standards are open, as otherwise a proprietary standard by certain manufacturers may lock Ruter in to a certain system, which could reduce flexibility and increase costs.

Technological development of hydrogen refueling stations (HRS) has made significant advancements since first deployments. Today, refueling times of 7 – 10 minutes per tankful can be guaranteed, thereby providing fuel cell buses with a considerable competitive advantage as compared to battery buses as alternative zero emission powertrain.

Several HRS for both buses and passenger cars have been installed in a number of countries and current ambitions aim at the establishment of widespread HRS networks. Therefore, HRS technology can be considered as being sufficiently mature, even though several areas for improvement remain: A higher number of installations in the future require introduction of technical standards for HRS in terms of provided hydrogen purity, accuracy of measurement of dispensed fuel and its temperature levels.

3.3.2.2 Reliability of infrastructure solutions

Biofuel infrastructure is considered reliable due to mature and developed technology. Overnight charging systems and other infrastructure solutions for overnight depot charging is developed and relatively mature. The most critical aspects include sufficient capacity of power to the depot, and scaling the system to ensure sufficient charging of the number of buses. This will drive investments, but can provide a highly reliable system[105].

For opportunity charging, the (inverted) pantograph is deemed to be the most reliable system. Inductive charging has so far not been operationally piloted in climatic conditions such as Oslo[106].

Since their first deployment in the CUTE project, hydrogen refueling stations (HRS) show high availability levels. Availability levels need to be maintained also when it comes to deployment of larger fleets of FC buses. Not only is the potential impact on public transport service provision of station downtimes even higher, but increase compressor redundancies overall investment costs significantly with each new station installed and is the use of public stations for passenger cars as an emergency alternative limited due to the different dispensing pressure levels used.

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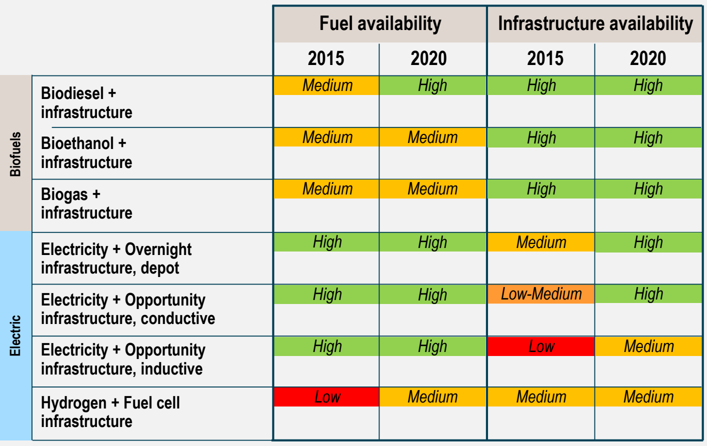
[100] Bombardier interview and input - [101] Bombardier and IPT Technologies - [102] Interviews with ABB and Opbrid -
[103] Oprid interview - [104] Interviews - [105] Interviews - [106] Interviews



		Fuel availability		Infrastructure availability	
		2015	2020	2015	2020
Biofuels	Biodiesel + infrastructure	Medium	High	High	High
	Bioethanol + infrastructure	Medium	Medium	High	High
	Biogas + infrastructure	Medium	Medium	High	High
Electric	Electricity + Overnight infrastructure, depot	High	High	Medium	High
	Electricity + Opportunity infrastructure, conductive	High	High	Low-Medium	High
	Electricity + Opportunity infrastructure, inductive	High	High	Low	Medium
	Hydrogen + Fuel cell infrastructure	Low	Medium	Medium	Medium

Figure 44: Fuel and Infrastructure availability overview[107]

3.3.3 Availability assessment summary

Figure 44 shows potential availability of fuel and infrastructure in Oslo 2015 and 2020. High fuel availability means fuel for more than 400 buses. High infrastructure availability means standards in place, as well as high operational reliability and existing well-designed after-market. The grading for biofuels is made with regards to high quality biofuels, as discussed in previous sections. To validate how many buses that can be supplied from one supplier, discussions need to be held with the supplier.

3.4 Environmental performance

KEY MESSAGES

- When considering buses with Euro VI–engines, the main focus should be on well-to-wheel CO2-emissions as PM and NOx-emissions are on very low levels
- Regarding biofuels, the CO2 impact is highly dependent on feedstock used and evaluations should ideally be conducted on specific fuels with known origin, production and transport specifications - 2nd generation biofuels preferred
- Fully electric and fuel cell buses powered by wind and hydro power energy have the lowest WTW CO2 – emissions, followed by PHEVs and HEVs. Among the biofuels, biogas from waste in Oslo has the best CO2-impact but biodiesel and bioethanol could reach almost similar levels

With regards to environmental performance, it is important to point out that all powertrain solutions have an environmental impact to some extent.

There is no solution that is completely emission-free and sustainable when the whole lifecycle of a fuel is considered. For example, an electric bus has no local emissions (NOx, PM) and no tailpipe CO2-emissions during driving. However, if the environmental impact from a lifecycle perspective (well-to-wheel) is analyzed there might be CO2-emissions in the production and/or transportation of the fuel. Therefore, renewable fuels do not necessarily imply zero emissions due to CO2-emissions from feedstock cultivation, production and transport processes of the fuel. The environmental aspects to be evaluated in this chapter are Green House Gas-emissions, local emissions (NOx, PM), noise and the use of scarce resources.

Well to wheel (WTW) reflects the total CO2-emissions generated in production, refining, transport as and consumption of fuel. Tank to wheel (TTW) emissions, or tailpipe emissions, exclude the CO2 generated before the energy reaches the vehicle. A Well to wheel perspective enables more accurate comparison of different technologies and more precisely present the total environmental impact of a certain fuel. The well to wheel analysis in this report does not include bus and infrastructure production and is not to be seen as a whole life-cycle perspective with regards to bus manufacturing and infrastructure production. Battery production is included in the CO2-analysis on a discussion basis, please see chapter below.

3.4.1 Well-to-wheel GHG Emissions

There are more GHG-gases than CO2 but since CO2 is the predominant greenhouse gas, greenhouse emissions factors are usually quantified in CO2 equivalents (CO2e) where all major GHG-gases are included.

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[107] Study analysis, interviews - [108] Clean Fleets, 2014

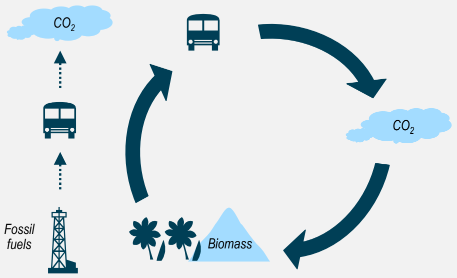


Figure 45: CO2-emissions from fossil and biofuel [%] [109]

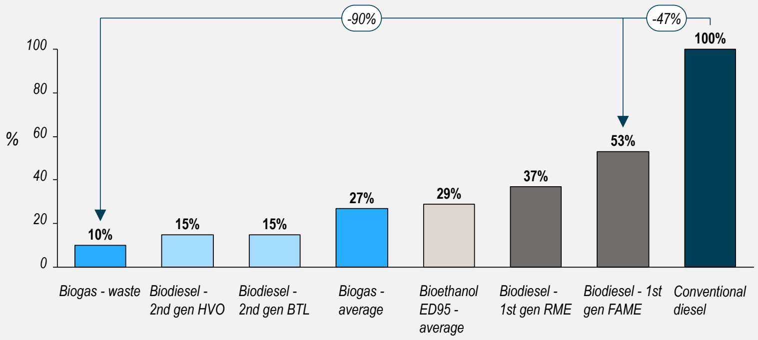


Figure 46: Average WTW CO2 emission reduction of various biofuels [%][111]

When consumed in bus engines, biofuels emit tailpipe greenhouse gases, similar to fossil fuels. However, as the organic material used to produce biofuels absorbs CO2 when it grows/is produced through the photosynthesis process, the total amount CO2 added to the atmosphere is lower than the amount of CO2 added from fossil diesel[108]. This is why biodiesel sometimes is referred to as a carbon neutral fuel, because CO2 have been absorbed when the biomass is growing and then released again, see figure 45.

CO2-emissions from biofuels vary significantly depending on the feedstock used. Well-to-wheel CO2-emissions from biofuels compared to conventional diesel had a reduction of between 21-65% for first generation biofuel and 50-95% from second generation biofuels. In figure 46, average CO2-emission reduction compared to conventional diesel is presented[110].

The difference in emission reduction is also high within each biofuel category, especially within first generation biofuels. Soy oil as feedstock has approximately 21-30% reduction, rapeseed 38-62%, palm oil 49-56% and sugar 52-71%[112]. In the production of Danish rapeseed, it is common that artificial fertilizers are used which is based on natural gas (not fossil free). Further, in some FAME-rapeseed production, 10-15% methanol, based on natural gas, is used in the production.

First generation bioethanol reductions vary from 37%-47% for corn and wheat as feedstock to 52-71% for sugar as feedstock[113]. According to the BEST-project, a four-year project supported by the European Union for promoting the introduction and market penetration of bioethanol as a vehicle fuel, the best kind of bioethanol with regards to CO2-emissions in 2009 was the bioethanol produced from sugarcane in Brazil. Since then, a second generation bioethanol from forestry feedstock has been developed with a CO2-reduction of 85-87% according to two Nordic suppliers, see previous chapter.

Biogas provides high GHG savings but is dependent on the production process. If the gas is produced far away from the usage, there will be GHG-emissions connected to the transport of the gas. The lowest biogas GHG-emissions come from biogas produced from organic waste (approximately 90% reduction compared to conventional diesel). This kind of biogas is available in Oslo and is beneficial from a CO2-impact standpoint.

Due to these variations in quality of biofuels, the European Union has issued new legislation. The aim of the legislation is to guarantee that European biofuels are sustainable and that the negative impact from using certain first generation biofuels is minimized. The legislation states that biofuels must reduce GHG-emissions well-to-wheel by at least 35 % compared to conventional diesel in 2015, and 60% in 2018 in order to reach EU renewable targets[114]. Most first generation biofuels will not fulfill these requirements and therefore primarily second generation biofuels are of interest with regards to what fuel to use in 2020.

A hybrid bus combines electric drive with usage of a biofuels. The extent to which the electric engine can be utilized is highly dependent on the duty cycle, driver efficiency, traffic and topography

[109] Source: Roland Berger - [110] VTT Technology, Nylund & Koponen, 2012, Cleen Fleets, 2014 - [111] Source: Study results, Desktop research, Roland Berger - [112] Study results, data from various reports and interviews - [113] Thema Consulting, 2015
[114] EU, 2009

of the route. The electric engine is mostly useful in urban traffic where the bus has frequent speed changes[115]. With a plugin hybrid, the electric utilization can be even higher and thereby reduce CO2-emissions significantly. A plugin hybrid bus with biogas as secondary fuel is one of the best hybrid powertrain solutions available from a CO2 perspective, see figure 47 later in this section. However, biogas hybrids are not estimated to be commercially available until 2022-2023 according to bus manufacturers.

An electric bus generates no CO2-emissions during driving and therefore the CO2-emissions are solely dependent on the production and transportation of the electricity. If Norwegian electricity produced from renewable energy sources is used, the WTW CO2-emission is almost zero. If Euromix electricity is used, the WTW CO2-emissions are similar to driving a Euro VI biodiesel bus or a bioethanol bus. However, when taking battery production into consideration it is realistic to assume that some fossil fuels have been used in the production and therefore a fully electric bus still has some WTW CO2-emissions. The degree of CO2-impact from battery production depends on aspects such as where the battery is produced and how the battery material extraction is conducted. Interviews indicate CO2-impact from battery production of about 10-20 ton for a 100 kWh battery[116].

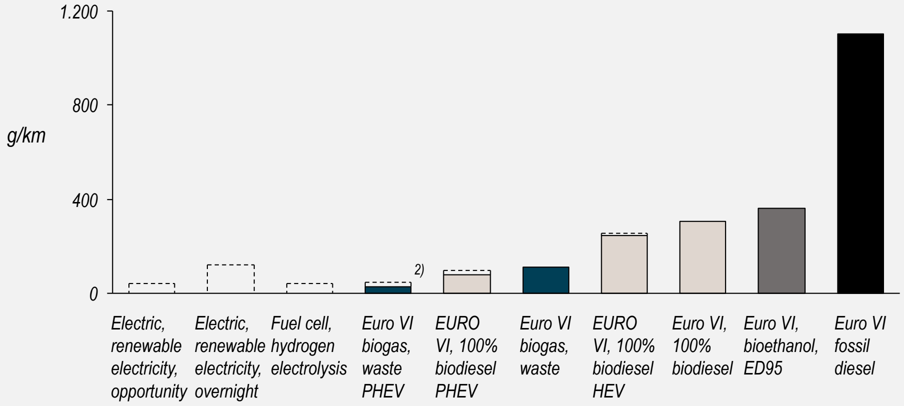
For fuel cell buses, WTW CO2 emissions are completely dependent on the H2 production method. Fuel cell buses have no CO2 tailpipe emissions, but might have WTW CO2 emission depending on the production method of the hydrogen used as fuel. If H2 is produced from electrolysis on site (as currently the case for Ruter), any CO2 impact only stems from the CO2 footprint of grid electricity. As this is very low in Norway (approx. 15 g/kWh) due to the high share of hydropower, the resulting WTW CO2 footprint of FC buses is also very low with the potential to become zero if electricity is provided from 100% renewable energy sources. If larger quantities of H2 are produced in centralized production facilities, additional CO2 emissions arise from delivery to the bus depot. If H2 is produced from biogas by steam methane reforming (SMR), WTW CO2 emissions are considerably higher, coming close to those of conventional diesel buses. If CO2 emissions from production of polymer exchange membrane (PEM) fuel cells used in automotive applications[117] as well as from production of the batteries used in the vehicles are considered, FC buses have a comparable CO2 footprint to battery opportunity buses. **SMR can be done on-site or off-site,** adding additional emissions if H2 is trucked from a central production plant. In the future, Carbon Capture and Storage (CCS) technology might be able also to reduce the CO2 emissions of steam methane reforming production to zero; but this technology will not be available until 2025 and it is questionable whether the WTW CO2 impact can really be considered as zero as CO2 is still produced. If H2 is sourced as an industrial by-product, CO2 emissions of the underlying production processes of the chemical industry will need to be analyzed individually. As by-product H2 normally stems from chemical production processes using electrolysis (but with different feedstock and end products) and the grid electricity CO2 footprint also applies here. In addition, other GHG emissions might be emitted from this production and the impact of the feedstock used needs to be considered. In general, the WTW GHG emission performance of by-product H2 is considered significantly worse than from other production methods.

Figure 47 next page is a schematic comparison of different powertrain solutions with regards to WTW CO2-emissions. Calculations are made for a 12 meter bus driven 55 000 kilometers per year. The dotted lines indicate potential impact from battery production and battery material extraction. The figure should be evaluated as a comparison and it is important to point out that the result can differ widely dependent on feedstock used for the various fuels. The values presented are based on a combination of results from bus manufactures, interviews with bio-fuel suppliers as well as information from reports.

In figure 47, electric powertrains have zero CO2-impact if battery production is excluded. This implies that Norwegian renewable electricity is used (and that renewable certificates are bought)[119]. If battery production is to be included, HEV, PHEVs and electric powertrains will be affected to various extents. The CO2-impact from battery production is considered linear with regards to battery size and therefore the overnight bus will have the highest CO2-impact due to larger batteries[120].

Levels of biodiesel, bioethanol and biogas in the figure can vary to a high extent depending on feedstock used and fuel production methods. Biogas from waste has the lowest impact among the biofuels when combining information from bus manufacturers and reports (although biogas hybrids are not estimated to be commercially available until 2022-2023). Biodiesel and bioethanol could reach almost similar levels as the waste-

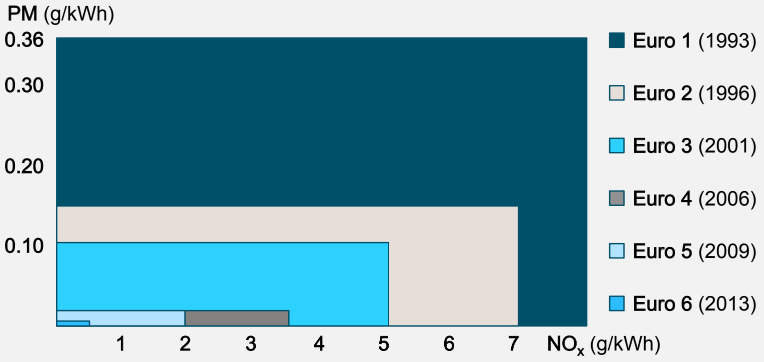
[115] Thema Consulting, 2015 - [116] Interviews - [117] Journal of Power Sources 159 (2006)

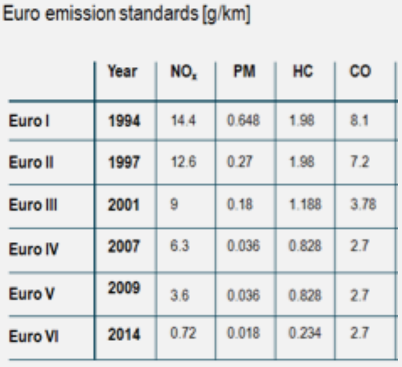


1) Annual emissions for a 12 meter bus driven 55 000 km
2) Biogas hybrids not available before 2022-2023 according to bus manufacturers
3) c.75% electric driving is assumed for PHEVs
Source: Bus manufacturers, interviews, TØI, Roland Berger

Dotted lines indicate CO2 emissions for battery and fuel cell production, although not part of a WTW assessment. Therefore electric drive imply zero WTW CO2-emissions

Figure 47: Well to Wheel CO2e emissions per km for various powertrains, a 12 m bus driven 55 000 km for one year [g/km] [118]





Euro emission standards [g/km]

	Year	NO_x	PM	HC	CO
Euro I	1994	14.4	0.648	1.98	8.1
Euro II	1997	12.6	0.27	1.98	7.2
Euro III	2001	9	0.18	1.188	3.78
Euro IV	2007	6.3	0.036	0.828	2.7
Euro V	2009	3.6	0.036	0.828	2.7
Euro VI	2014	0.72	0.018	0.234	2.7

Source: Embarq 2013, VTT 2012

Figure 48: Euro emission requirements [121]

based biogas but the uncertainty is higher than for the biogas which is already on place in Oslo. The pure biodiesel used in the calculations instead have 70-80% CO2-reduction which is currently reasonable according to bus manufacturers and interviewees. However, better biodiesel exist according to biofuel suppliers but is not verified by CO2-emission information from bus manufacturers. Bioethanol has higher WTW CO2-impact than the pure biodiesel mainly due to fossil content in the additive and uncertainties regarding the CO2-impact from Borregaard.

3.4.2 Local Emissions

Particulate matter (PM) and Nitrogen oxides (NOx) emissions have been the key focus of recent international emission standards and can cause health issues. European Union have declared upper limits for local emissions, see figure 48. The legislation regarding PM and NOx have been in force since 1993-1994 and the requirements have been more and more rigorous for each new Euro-requirement. A Euro VI engine should in theory reduce local emissions to negligible levels[122] and the difference is significant compared to Euro V. Buses with Euro VI engines have impressively low emissions and the emissions of NOX and PM are comparable with those of a diesel Euro VI private car[123].

Biofuel buses will follow the Euro VI emission standards and thereby have local emissions in line with the standard requirements for fossil diesel. Local emissions for biogas buses will be lower than Euro VI diesel buses, both for NOx and PM. 30% reduction of NOx has been measured compared to Euro VI diesel engines[124], see figure 49 next page. Data for ED95 bioethanol is limited since no Euro VI bus exist but local emission will be in alignment with Euro VI according to bus manufacturers.

[118] Source: Bus manufacturers, interviews, TØI, Institute of Transport Economics, Norwegian Centre for Transport Research, 2014, Roland Berger - [119] The current CO2 footprint of electricity from the grid is about 15 g/kWh in Norway which is very low compared e.g. to Germany (500 g/kWh). Therefore, Norwegian grid electricity is not completely CO2-free, but has been considered so as Ruter buys electricity certificates to compensate for the remaining CO2 impact. - [120] Estimation of 0.5 g/kWh battery per km assuming battery is used 5 years, source: interviews, USF, 2014 - [121] Volvo - [122] Clean fleets, 2014 - [123] https://www.toi.no/getfile.php/Publikasjoner/T%C3%98I%20rapporter/2013/1291-2013/1291-2013-sum.pdf - [124] Miljødirektoratet (2014): Grenseverdier og nasjonale mål. Forslag til langsiktige helsebaserte nasjonale mål og reviderte grenseverdier for lokal luftkvalitet. M-129 – 2014.

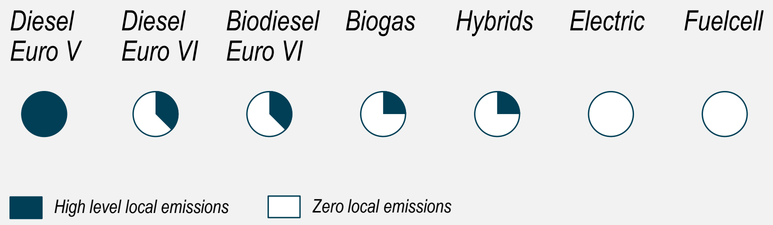
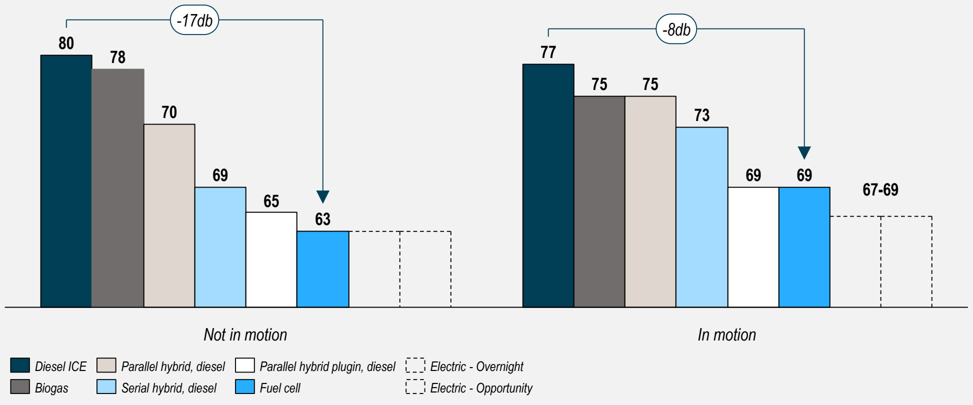


Figure 49: Local emissions (NOx, PM) for various powertrains compared to Euro V standard



1) Nonlinear db scale; -10db = 50% noise

Figure 50: Noise levels for various powertrains [125]

Electric and fuel cell buses emit zero local emissions. A hybrid bus is also emission-free when driving on electric power only but generates emissions depending on which secondary fuel is used. Since the hybrid is charging the battery during braking and driving down slopes, it is possible to decide when to drive in full electric mode. For example, it is possible to use only electrical power and have zero emissions in sensitive and populated areas (zone management). Although the local emissions from a bus can be zero, it is important to remember that all vehicles produce PM-emissions to some extent by road wearing, although in very small quantities.

3.4.3 Noise levels

The noise levels from different powertrains are primarily important in slow moving and still standing city traffic. Here the noise affects many people and should be minimized.

The noise levels from the different fuel types will primarily depend on the engine technology, see figure 50.

Biogas buses have lower noise levels than diesel buses while electric and fuel-cell buses are the quietest ones. Average decrease in noise pollution between electric buses (including fuel cell buses) and conventional diesel buses is 12.5 db which equals around 57% decrease[126]. Parallel plugins also have low noise levels according to bus manufacturers. Studies show that both passengers and inhabitants in cities appreciated electric buses due to reduced noise levels[127].

Regarding bioethanol, previous tests at Ruter have shown that noise levels are low outside the bus but higher than diesel engines inside the bus. This is due to low frequency noise that goes through the windows.

3.4.4 Use of scarce resources/hazardous materials

Land use for first generation biofuel is controversial. For first generation biofuels, there is a constant discussion regarding the use of various feedstocks. The land and some of the feedstock could have been used for food instead of fuel which is controversial. The indirect land use change impacts (ILUC) of biofuel is the unintended consequence of releasing more CO2-emissions due to indirect land-use changes when croplands for ethanol or biodiesel production are expanded and replace other crops and vegetation.

First generation biofuels might impact existing ecosystems. The European Commission has run 15 studies on different biofuels crops and concludes that on average over the next decade, Europe's

[125] Pilots and trials, Bus manufacturers, FCH JU, 2012 - [126] FCH JU, 2012 - [127] Trafikförvaltningen i Stockholm, 2015

biofuels policies might have an indirect impact equal to 4.5 million hectares of land (an area the size of Denmark). The cultivation of crops specifically tailored for biofuels may also be damaging to the existing ecosystem and could also decrease global biodiversity.

First generation biofuels also increase food prices. The UN Food and Agriculture Organization estimated in 2008 that biofuels accounted for approximately 10% of the recent food price increases around the world. This is partly due to the fact that some farmers will switch from producing food to produce biofuels if this is more profitable and if fewer farmers are producing food the price of food will increase.

Battery recycling is of high priority. For batteries, the recycling of spent batteries and the battery production are the most important aspects with regards to environmental concerns. Since scarce metals in batteries (such as lithium) are not consumed during the battery lifetime, a sustainable process for re-using and recycling batteries is important[128]. In general, Li-ion batteries have more safety challenges than nickel and lead-based batteries mainly due to their organic electrolyte and relatively high energy content. It is particularly important that the cell voltage ranges as well as operating temperatures are controlled. Overcharging caused by exceeding specified thermal limits may cause critical thermal events. Therefore, a highly reliable battery management system is required to protect against overcharge and maintain safe operating conditions[129]. Since the battery material is contained, there are no toxic concerns during usage or handling of the batteries. However, in case the battery container is broken, for example in a fire, there might be toxic gas leaks. The fire department in the region should have know-how about battery usage in the buses[130].

3.5 Operational performance

KEY MESSAGES

- Sound assessment of operational performance of different powertrain solutions and matching with Ruter's operational requirements are key to evaluate the impact of large-scale deployment of innovative solutions
- Due to significantly lower energy density for batteries compared to diesel, about 8-10 times more weight is needed for electric buses (batteries) compared to diesel (fuel tank)
- Energy consumption reduction compared to biodiesel is about 60-70 % for electric buses and about 20-35% for hybrids
- Overnight buses typically charge in full, opportunity charged buses may have constraints in charging time and thereby the amount it can charge (and thereby range)
- The driving range without refueling/recharging for different powertrains varies but an average range for an overnight bus is about 240 km and for an opportunity bus about 20-40 km
- Current passenger capacity for a fuel cell bus is c.80% of an equivalent biodiesel bus and c.85% for an overnight bus and c. 95% for an opportunity bus compared to an equivalent biodiesel bus
- Bus uptime is lower for overnight, opportunity and fuel-cell buses (currently c.80% compared to 98% for diesel buses) but estimated to be

3.5.1 Energy density, efficiency and fuel consumption

Different fuels vary in terms of energy density (energy relative volume and weight) and powertrains differ in energy efficiency (fuel consumption per km). The differences have high impact on important operational parameters such as driving range and passenger capacity. Energy density is important since there are both volumetric and weight restrictions on a bus. Hence, low energy density means more fuel volume needed on the bus, less driving range and optionally less passenger capacity.

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[128] Interview with Eurabat, 2015 - [129] Eurabat et al, 2015 - [130] Interview with Eurabat, 2015

3.5.1.1 Energy density

Energy density is an important parameter for bus fuel since there are both volumetric and weight restrictions on a bus. Low energy density means more fuel volume is needed on the bus. As seen in figure 51, biodiesel has high energy density compared to electric batteries.

Biodiesel has high energy density, which enables long driving range without refueling. The differences in energy density have significant impact on the driving range and there is a direct correlation between the driving range of a bus and the energy density of the fuel. Conventional diesel powered buses have a great practical advantage because of very high energy density that allows a great driving range per full tank[132]. A biodiesel bus has an average driving range of about 600-700 km on a biodiesel tank that weighs about 250-350 kg. An electric overnight bus has a driving range of 100-300 km on a 2000-3000 kg heavy battery pack [133]. This weight difference affects the passenger capacity and/or the fuel consumption of the bus. Biogas fuel has an energy density between diesel and electricity and therefore a larger gas tank is needed compared to a diesel tank in order to have the same driving range.

3.5.1.2 Energy efficiency and fuel consumption

The energy efficiency increases with the use of electricity as fuel. Pure electricity drive requires only 25% of the diesel energy consumption according to Volvo, see figure 52.

This ratio from Volvo is not certain however, and according to other bus manufacturers and trials, electric driving consumes about 33% compared to biodiesel, see figure 53 below. Heating in electric buses, if using battery, will increase energy consumption by c. 20-30%. According to Hamburg trial, when using the HVAC system, buses consume →2 kWh/km of electricity from the battery. More likely is to use a biofuel heating generator (which would make the electric bus not completely emission free although the levels are low).

Bioethanol fuel consumption is about 1.6 times the biodiesel consumption; although there are no Euro VI bioethanol buses currently available and hence no available fuel consumption data. Fuel consumption for PHEVs can vary significantly depending on the degree of external charging.

Also the production of fuels requires energy. If hydrogen is produced from electrolysis, about 60% of the energy consumed by the electrolyser is transferred into the hydrogen produced – this means that the energy efficiency of hydrogen production is limited.

3.5.1.3 Energy assessment summary

Although electricity has three-four times higher energy efficiency, the difference in energy density is so large that batteries still are inferior with regards to km driven per fuel weight or fuel volume. A diesel tank of about 300 liters is comparable to a battery pack 8-10 times larger, see illustrative figure 54.

Battery electric buses need to operate large parts of the day to leverage high energy efficiency and low price of electricity.

3.5.2 Driving range and technical performance

Actual range in km for different powertrains depends on the actual fuel consumption in Oslo/Akershus which is impacted by different factors such as route topography, driving patterns, HVAC (heat ventilation and air conditioning) need in winter/summer time and bus battery size. These have higher impact than the bus type (12 meter, 13-15.5 meter, 18 meter) and there are no reported differences in driving range according to input from bus manufacturers.

[131] Source: Cenex data - [132] U.S. Energy Information Administration, 2014 Thema Consulting, 2015 - [133] Interviews, bus OEMs
[134] Source: City Mobility Transport Solutions, Volvo

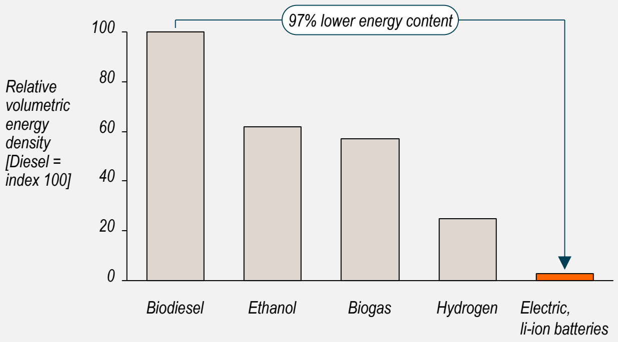
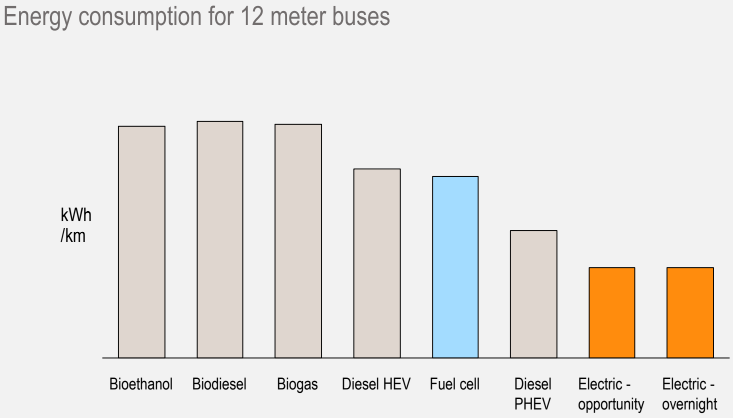


Figure 51: Energy density per fuel, biodiesel = index 100. A higher energy density index is better.[131]

	Fuel kWh/km	Electricity kWh/km	Energy total
Diesel	*5.0*		*100%*
Hybrid	*3.1*		*61%*
Electric hybrid	*1.0*	*1.0*	*40%*
Electric		*1.25*	*25%*

Figure 52: Energy efficiency for various fuels[134]



Conversions: 1 liter diesel = 9.8 kWh, biogas: 1,25 kg/Nm³, 1 Nm³ biogas (97 % methane) = 9.67 kWh, Hydrogen: 33,33 kWh/kg

Figure 53: Energy consumption for 12 meter buses[135]

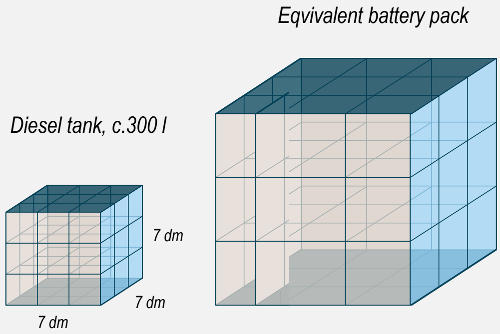


Figure 54: Volume comparison diesel tank versus battery pack [136]

Biodiesel and hybrid buses have the same range in general, see figure 55. Bioethanol and PHEV buses have slightly reduced driving range. Biogas buses have the same driving range as biodiesel buses according to bus manufacturers but according to Ruter data and experience, the range is about 350 km. Overnight charged buses have an average range of about 240 kilometers without refueling whereas opportunity buses have significantly lower range without refueling, about 20-40 kilometers. HEVs usually have better range capabilities than PHEVs as shown in figure 55.

PHEVs have the possibility to use more pure electric driving compared to HEVs by using external charging. With additional charging of a PHEV during the day, additional driving range of 12-20 km extra pure electric drive can be achieved, depending on charging time and capacity of the charger. One benefit of PHEVs compared to fully electric buses is that a higher proportion of the battery capacity can be utilized given the second power system (ICE), and thereby a lower need to maintain battery power for back-up purposes (such as traffic stall). Another experience from Hamburg trial is that the more pure electric driving that can be achieved with the PHEV, the lesser heating is achieved in the conventional ICE engine, which might cause problems in reaching EURO VI emission standards.

Battery opportunity buses only have a very limited range without recharging. Hamburg trial assumes that about 60% of the total battery capacity in a battery bus can actually be used and determine the range of vehicles – rest is buffer in case buses get stuck in traffic and to save battery lifetime. Fuel cell buses have a longer range and currently reach about 220 km in Oslo, although 300 to 450 km is reported from bus manufactures and other trials. If the full potential of driving range for fuel cell buses can be realized, this is a major operational advantage of these buses compared to battery vehicles. Average maximum driving range in pure electric drive is presented in figure 56.

[135]Source: OEM and pilot results - [136]Source: Roland Berger - [137]Source: Bus OEMs and pilots - [138]Source: Bus OEMs and pilots

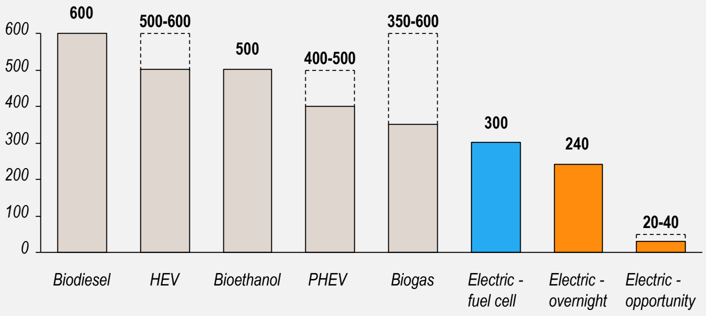


Figure 55: Range without refueling, average values [137]

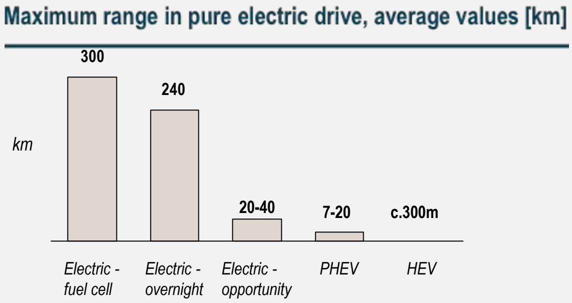


Figure 56: Pure electric drive (without recharging) for various powertrains [138]

Opportunity driving range depends on charging time and charging power. High charging power enables faster charging; see indicative kilometers per charging minute in figure 57.

Important to point out is that these numbers are indications and actual driving ranges achieved by opportunity charging also depends on other factors. Most notably, the state of charge (SOC) level of the battery is a potentially limiting factor of charging speed as well as the battery technology used in the vehicle. Whereas higher charging powers are not so much a challenge from an infrastructure point of view, feasible maximum recharging power is limited by the maximum power available battery technologies can accept and the degree of their degradation through high power recharging.

3.5.3 Route flexibility and topography performance

All solutions have full flexibility in changing routes and detours (limited by their maximum daily ranges) except for battery opportunity buses which need to stop at fixed recharging points regularly. Between the charging points flexibility is only limited by the frequency of recharging stops.

3.5.4 Speed and acceleration

The maximum speed for opportunity and overnight buses is 75-85 km/h according to bus manufacturers. However, there are no technical limitations for electric engines to have maximum speed similar to ICEs, it is only a matter of speed configuration reported by the bus manufacturers. Speed and acceleration can be optimized to save the battery and to fit the driving cycles required. For biodiesel, bioethanol and biogas buses the maximum speed is about 100 km/h and hybrids ranges from 80-100 km/h in top speed. All powertrain solutions are estimated to fulfill the requirement of 80 km/h in maximum speed. There are no major differences between the different solutions on acceleration according to bus manufacturers.

3.5.5 Passenger capacity

Average bus capacity is an indicator of the typical size of the bus in use. Capacities can range significantly, from around ten passengers in a minibus to around 200 in an articulated bus. Bus passenger capacity highly depends on seat layout and number of standees per square meters, also being limited by maximum allowable vehicle weight. Ruter uses three standing passengers per standing area square meter.

Biodiesel, biogas and bioethanol solutions can in general carry the same amount of passengers; variance is primarily given by different bus layouts. Limitations have to be considered for fuel cell buses however as the required powertrain components and fuel storage require substantial space and additional weight (about 80% capacity compared to a biodiesel bus).

Furthermore, battery overnight buses have capacity limitations. This is due to the high weight of the large battery that needs to be carried (due to low energy density of batteries). The passenger capacity is estimated to c.85% of the capacity of a biodiesel bus[140].

Opportunity buses currently have a passenger capacity between biodiesel and overnight buses but the capacity is estimated to converge with biodiesel capacity in the future due to battery developments. Several bus manufactures have the aim of equal weight of an electric engine and an opportunity battery pack compared to the weight of a diesel engine, tank and gearbox when the buses are launched. However, today, the capacity of an opportunity bus is about 95% of a biodiesel bus[141]. Interviews suggest that passenger capacity for opportunity buses might be slightly lower for 18 meter buses (c. 94%).

Figure 58 summarizes the potential losses in passenger capacity compared to ICEs when introducing new technologies.

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[139] Source: Bus OEMs and pilots - [140] Bus OEMs - [141] Interviews - [142] Source: Bus OEMs and pilots

Charging power [kW]	Battery charging power [kWh]	km per charging min, 12 m	km per charging min, 13-15.5 m	km per charging min, 18 m
100	100	c1.1	c.0.8	c.0.7
300	300	c.3.3	c.2.5	c.2.2
600	600	c.6.7	c.5	c.4.3

Bus length	Energy consumption [kWh/km]
12m	1,5
13-15.5m	2
18m	2,3

Figure 57: Examples of opportunity driving ranges per charging minutes[139]

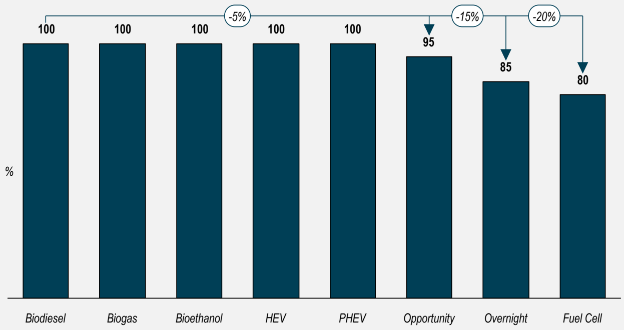

Figure 58: Estimated passenger capacity index by powertrain[142]

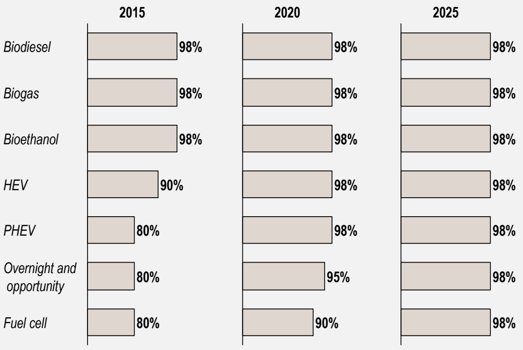

Figure 59: Estimated uptime for various powertrains in time of commercial readiness [%][143]

Reduced passenger capacity implies additional buses may be required, if load factors are to be kept constant and the same number of passengers are to be transported. This has implications for total costs of introducing new technologies. According to Hamburg trial, keeping productivity at the same levels is key for long-term success of a technology – deploying more buses because of the specific limitations of a technology is not considered a viable option.

In 2020, passenger capacity for opportunity buses is estimated to be at same level as for an equivalent biodiesel bus. In 2025, passenger capacity for overnight buses is estimated to be at same level as for an equivalent biodiesel bus. Fuel cell buses however, are not indicated by interviews to have equal passenger capacity as an equivalent biodiesel bus in 2025.

3.5.6 Reliability and uptime performance

Powertrain solutions vary in uptime and reliability. In general, the reliability is low in early phases when implementing a new emerging powertrain technology. The definition of 'uptime' includes both scheduled maintenance and unscheduled breakdowns. Estimated uptime for various powertrains is related to the timing of commercial readiness according to bus manufacturers as presented in figure 59.

Overnight, opportunity and fuel cell buses have lower uptime compared with traditional powertrains in 2015. Before 2025 however, it is reasonable to assume that the uptime will be identical to diesel buses. The main reasons for the low uptime of electric buses are immature supply chains leading to limited availability of spare parts and also issues regarding infrastructure downtime[144].

Input from the public transport in Stockholm indicates lower reliability and uptime of bioethanol buses and the city reports problems with maintenance. Bioethanol buses in Stockholm have higher scheduled maintenance and this make some operators to partly shift to biodiesel buses instead.

New statistics from other trials in Europe (more than 150 buses analyzed) indicate uptimes of 90-98% for diesel buses, 91 % for parallel hybrids, 82% for serial hybrids and 67-80% for full electric buses[145].

Limited vehicle uptime is currently a problem also for large-scale deployment of fuel cell buses. Whereas first generation fuel cell buses reached relatively high availability levels of about 82% on average in the CUTE project and up to 92% in HyFLEET:CUTE. However, reported levels dropped in the CHIC project where they ranged between 40 and 80%, being on average below the project target of 85%. In the last months of the projects, improvements could be achieved and technological problems be alleviated so that there is a promising perspective for further improvements in the coming years.

3.5.7 Expected development until 2020

Operational performance specifically needs to be improved for innovative concepts like overnight, opportunity and fuel cell buses. Slight improvements in terms of fuel economy and larger ones in availability are expected for fuel cell buses and significant improvements are expected for battery performance in terms of weight to be reduced and energy density to be increased allowing for larger daily ranges.

For electric buses, up to c. 20% improvement in performance (kWh/kg battery) could be expected to 2020. However, this will be from a low base in terms of daily range.

[142] Source: Bus OEMs and pilots[143]Source: Bus OEMs and pilots - [144]Interview with German Association of Transport Companies (VDV) - [145]Hybrid- und Elektrobus-Projekte in Deutschland. 2015

3.6 Economic performance (costs)

KEY MESSAGES

- Future developments of the initial purchasing costs of plug-in hybrid, electric and fuel cell buses as well as prices for biofuels are highly uncertain and depend on future market developments
- Biodiesel ICE and biodiesel hybrid solutions are expected to be the least costly renewable powertrain options also in the long-term
- Bioethanol buses are expected to have a limited price premium compared to biodiesel
- Biogas buses are the most expensive of all biofuel solutions while offering the greatest CO2 reductions of all biofuels
- If costs are adjusted for incurred downtime, reduced passenger capacity as well as more buses needed due to opportunity charging times, overnight and opportunity e-buses are more expensive than biodiesel buses also in the longer term
- Costs for plug-in hybrid buses largely depend on their way of usage: If charged on the route by opportunity charging, their costs are even higher than for electric buses; if only charged at depots during the day, their costs are substantially lower
- Fuel cell buses are the most costly powertrain solution in terms of overall TCO, bus and infrastructure purchasing prices
- Given that labor (drivers) account for c. 70% of TCO, a main driver for significant TCO differences is the need for extra buses on the route due to reduced passenger capacity or opportunity charging times

3.6.1 Introduction

Future costs of nascent technologies are highly uncertain. Bus purchasing costs are a major factor influencing overall TCO. Today, plug-in hybrid, electric and fuel cell vehicles are significantly more expensive than conventional ICE buses, but the future development of their prices is dependent on a number of factors:

- Further technological development
- Cost reduction potential for key components (mainly batteries and fuel cells)
- Overall market development
- Future regulatory requirements (e.g. fuel taxation)

All above points highly impact costs, but with limited visibility of their future development. The same applies for future infrastructure costs for all innovative technologies: Installations have only been made to a very limited extent and future developments and realization of potential scale effects are unclear at the moment.

Longer operational experience with maturing technologies is limited and the associated cost impacts are not fully predictable today. Such buses have never been operated over a full life-cycle so far, and therefore lifetime maintenance costs, durability of key components and actual fuel consumption under specific local conditions in Oslo and Akershus are largely unclear. This is reflecting the current development stage that these technologies have reached: They are in a pilot phase where they are being tested in normal daily operations, but so far only with a limited number of buses. Experience under Nordic conditions specifically is missing so far, and potential costly adaptations to vehicles, infrastructure, fuels etc. cannot be fully understood at the moment.

Cost assessment have been performed using the "Total Cost of Ownership (TCO)" approach with some amendments: In the TCO approach, bus costs are being analyzed on a "per km" basis, i.e. all incurring costs for operation of a bus in one year are divided by the total annual mileage of the bus. This ensures comparability of costs between different powertrain options. Costs taken into consideration in this report for TCO calculations are the following:

- Bus depreciation costs (including financing costs)
- Bus maintenance costs (including replacement costs for batteries and fuel cells where applicable)
- Fuel costs
- Infrastructure depreciation (incl. financing), maintenance and operational costs
- Labor costs for bus drivers, bus servicing and cleaning
- Downtime costs (costs incurring for additional

replacement buses needed because of reduced availability of some technologies)
- Reduced passenger capacity costs (costs for additional buses needed in the fleet if technologies with reduced passenger capacity are being deployed)
- Costs for additional buses needed to keep current schedule if buses need to be recharged during the day on the route

This means that in the approach chosen in this report, costs for additional buses needed to replace buses with reduced availability are part of overall TCO costs. In addition, costs for additional buses and drivers required due to reduced passenger capacity are also included in the TCO (e.g. instead of 10 buses to be deployed at standard passenger capacity, 12 buses are needed in reality to provide the same passenger transportation capacity). Due to the current operational setup at Ruter, additional buses will also need to be added to the fleet if newly deployed buses need to be recharged during the day by opportunity charging. As on most lines in Ruter's area of operation bus schedule frequencies are relatively high and normally no waiting time can be used for opportunity charging between bus cycles, opportunity charging causes a need for additional buses running on the lines to keep the same level of service. This applies for battery opportunity buses as well as plug-in hybrid buses in case they are operated also using oppor-tunity charging (such as in Hamburg or Gothenburg).

TCO calculations have been based on a number of assumptions reflecting local framework conditions at Ruter:
- Annual mileage of buses: 55,000 km as in current Ruter fleet
- Bus lifetime: 10 years as per current contract regime
- Infrastructure: 20 years for established technologies, 15 years electric recharging infrastructure
- Bus uptime: Reduced for plug-in hybrids, electric and fuel cell buses until at least 2020
- Replacement buses: Biodiesel buses as least costly option
- Financing costs: 7%
- Labor costs: 3 bus drivers per bus in daily operations (without back-up buses)
- Depot charging infrastructure: Required for plug-in hybrid, overnight and opportunity e-buses
- Opportunity charging infrastructure: Required for plug-in hybrid and opportunity e-buses, 1 point can serve 6 buses
- Fuel prices: Based on 2015 levels including applicable road and CO2 taxes

Several factors can have a major impact on all TCO calculations and need to be considered when carrying out sensitivity analyses:
- Bus purchasing costs: Specifically for nascent technologies prices widely vary between different manufacturers
- Annual mileage: Increased mileage reduces costs, which can be a lever to reduce TCO of currently maturing technologies when maximizing their time in service
- Financing costs: Access to cheaper financing can reduce overall TCO especially where high investments in buses and infrastructure are required
- Infrastructure costs: The more the buses use the infrastructure installed, the cheaper the infrastructure cost per bus – Where possible, concentration of infrastructures should be aimed at
- Volume discounts: Purchase of larger bus numbers and larger infrastructure installations might offer volume discount potentials
- Fuel prices: Fuel costs are a significant part of overall TCO, but can widely vary for alternative fuels depending on future market developments
- Bus lifetime: Longer bus lifetime has a positive effect on bus depreciation costs which might be a lever to reduce TCO specifically for electric powertrains which might be able to be operated on longer timeframes than conventional ICEs.

3.6.2 Bus purchasing costs

Bus purchasing costs for the different powertrain options differ widely, causing a large part of the TCO differences between the available solutions. Very high bus purchasing costs compared to conventional technologies specifically have to be encountered for innovative technologies such as battery electric or fuel cell buses, but also plug-in hybrids. In combination with the incurred financing costs for initial bus investments, high bus purchasing costs have a high impact on overall TCO. Potential additional variance in individual bus costs even of the same technology type are driven by customizations and specific requirements that different PTAs and bus operators apply to their buses (e.g. high capacity HVAC systems, telematics systems or other specific bus equipment). For 13-15.5 meter buses or 18 meter buses higher respective bus purchasing costs have to be considred compared to standard 12 meter buses, which are the main point of reference in the below description. However, the project has also assessed the other types.

Buses with conventional ICEs have the lowest bus purchasing costs, reflecting their level of technology maturity and market penetration. Biodiesel buses have basically the same purchasing costs as conventional diesel buses. Bioethanol buses are slightly more expensive (~5%) which is caused also by the fact that such buses are not widely used in Europe and currently only offered by one bus OEM. Biogas buses are of the same kind as conventional CNG buses and purchasing prices typically are identical. Gas buses are more expensive than ICE buses with liquid fuels, with a price premium of about 10-15%.

Standard hybrid vehicles are about 30% more expensive than conventional buses, plug-in hybrid vehicles have a price premium of up to 70% today. For standard hybrid vehicles costs can slightly vary depending on whether parallel or serial powertrain architectures are chosen. Such vehicles are today well-established and available in the market; a price premium compared to conventional buses will need to be regarded also in the mid to long-term as such vehicles have a more complex architecture with two different engines and integrated small-sized batteries. On the contrary, plug-in hybrid vehicles are still in a development phase at the moment and their purchasing price level is comparable to that of opportunity e-buses at the moment. These buses feature a larger battery than standard hybrids (but smaller than opportunity e-buses) causing larger vehicle costs. At the same time, they still have a conventional ICE integrated in the vehicle which adds costs in comparison to an e-bus which only has an electrical engine. Costs are expected to slightly decrease in the next years with dropping battery prices and further market uptake for plug-in hybrid vehicles.

E-buses are today about two times as expensive as conventional buses, with differences between overnight and opportunity e-buses. The main cost driver for these buses is the battery integrated in the vehicle as primary power source. As overnight e-buses have substantially larger batteries (~300 kWh) than opportunity e-buses (up to ~100 kWh), they are also more expensive in bus purchasing: Today, overnight buses cost about 220% of a conventional bus (battery represents ~40-50% of overall vehicle purchase costs), opportunity e-buses about 170% (battery represents ~25% of overall vehicle purchase costs). Although the battery size of an overnight e-bus is about three times higher, the price difference between the two types is limited by the fact that different battery types are typically used in the two e-bus version. Faster and more frequent recharging for opportunity e-buses typically requires a different and more expensive battery type than used in overnight e-buses. Expected cost reductions for e-buses are mainly driven by cost reductions for integrated batteries; these are expected to be at about 5% annually. Also in the long-term a price premium of about 30-40% for opportunity and 60-70% for overnight buses needs to be considered.

Fuel cell buses have the highest purchasing costs today, which are about four times higher than for a conventional bus. The purchase price of FC buses has fallen by about one half since their introduction about 10 years ago and it is expected to decrease further to approximately two times the price of a conventional bus in the year 2025. A considerable purchase price premium to the conventional buses is expected to remain even in the long term. Available analyses indicate that the costs of the FC bus powertrain components can come down considerably with an increase in unit volume of the fuel cell and battery passenger car market in addition. Due to high uncertainty in future market development and potential to realize synergies with passenger cars, fuel cell bus purchase cost development can vary significantly in the future.

3.6.3 Bus maintenance costs

Technologies based on ICEs have the lowest maintenance costs, but the costs for pure biodiesel (B100), biogas and bioethanol buses are slightly higher than for conventional diesel buses. Costs for biogas bus maintenance is slightly higher than for biodiesel buses. Bioethanol have more maintenance needs (~20% higher costs than biodiesel). It is expected that maintenance costs for these technologies remain more or less stable in the mid- to long-term. Due to a relatively low cost level for these maintenance costs, impact on overall TCO is relatively limited.

For hybrid vehicles a comparable level of maintenance costs can be assumed as for the respective ICE buses, dependent of which fuel is used in these vehicles (biodiesel or biogas). Plug-in hybrid vehicles have increased maintenance needs which are still difficult to estimate on a reliable basis as these vehicles are just being piloted today and are expected to be commercially available only by 2018-2019 by respective bus OEMs.

Electric and fuel cell buses have higher maintenance costs primarily because of the need for component replacements. Whereas maintenance costs for the base vehicle itself can be assumed to be lower than for conventional technologies as electric powertrains have lower maintenance needs, limited battery and fuel cell lifetime cause a need for replacement of key components during the assumed lifetime of the bus. As batteries and fuel cells are the most expensive individual components in these buses, maintenance costs increase significantly when factoring in component replacement costs. These assumed maintenance costs for such vehicles are highly uncertain as operational experience so far is limited and it cannot be said for certain which exact lifetime these components have and which exact costs are incurring due to their replacement. Whereas some bus OEMs claim that batteries do not need to be replaced at all, it seems more sensible to assume at least one replacement of batteries during the lifetime of the bus. As with future technology development the need for replacements is expected to decrease (or even to be completely abolished), it is expected that maintenance costs for electric and fuel cell buses will be reduced and even fall below levels of conventional ICE buses

3.6.4 Fuel costs

In Norway, several kinds of fuels are today levied with additional taxes which impact costs comparisons. As foreseen in the state budget for 2015, currently imposed road and CO2 taxes are as follows: Diesel is levied both types of taxes. Biodiesel is levied half "road- tax" but no CO2 tax. Bioethanol, electricity and hydrogen are exempt, see figure 60. Due to the current taxation regime the use of diesel as fuel is more expensive than the use of pure biodiesel so that there is currently no difference between diesel and biodiesel bus TCO – or even a more favorable cost for biodiesel.

	CO2 tax NOK / metric unit	Fuel / road tax NOK / metric unit
Diesel	0,68	3,82
Biodiesel	0	1,91
Biogas	0,66	0
Bioethanol	0	0

Figure 60: Overview of levied taxes by fuel[146]

At the moment, it is highly unclear how taxation will develop in the future. To a certain extent, it can be expected that it will be adjusted to the regulations stated in the EU's "Clean Vehicles Directive" (2009/33/EC), but that needs to be seen. Depending on the type of fuel used and the fuel consumption per km, fuel costs can constitute a larger part of overall TCO – therefore future taxation can have a high impact on future fuel costs developments. Specifically taxation of electricity and hydrogen, which are overall the most expensive technologies today, would have an unfavorable impact on their overall TCO.

For biofuels, future development of fuel prices is the major uncertainty when analyzing overall TCO. For these analyses, we are using 2nd generation of biofuels. Prices for these fuels as well as supply and demand largely depend on regulation regimes applied. In addition, price developments are dependent also on overall oil price developments which can make usage of biofuels more or less economic compared to conventional diesel. If Ruter requires larger quantities of these fuels in the future, another cost impact arises from the potential need for imports: As local supply is limited, additional costs might incur when fuels need to be imported from other European countries. Some biofuels also require dedicated financing, which adds to the costs.

Hybrid vehicles have about 20% reduced fuel costs and plug-in hybrids offer the potential for even larger reductions. Depending on the energy savings that can be realized from energy recuperation systems, standard hybrids can save c. 20% of the respective fuel costs per vehicle which to a large extent offset the initial higher investment in the bus. If plug-in hybrid vehicles are powered to a maximum extent by electricity (requiring opportunity charging infrastructure along the route), fuel costs can be reduced significantly more (e.g. if 75% of the kilometers driven are powered by electricity, and the other fuel is only used as a backup). On the other hand, high usage of electricity for plug-in hybrids triggers the need for adding more buses to the fleet, thus driving overall costs significantly.

Pure electric buses have the lowest fuel costs, as they have very high energy efficiency and use only electricity as fuel. Low electricity prices are obviously paramount for realizing significant costs savings on fuel for such vehicles, higher electricity costs can have a negative impact on overall TCO. Another decisive factor for electricity costs is the way in which the local utility charges its customers: Besides costs for pure consumption and grid usage, an additional fee is being added in Oslo/Akershus to the price per kWh for the provision of the maximum peak demand required. Thorough balancing of peak demand is therefore important to avoid high additional costs for electricity usage that is only occurring at very few times per day. Depot charging systems will therefore need to make most economic use of the time available for recharging to avoid high peak demands. The same applies to opportunity charging systems which have higher energy demands and therefore should be used to their largest possible capacity.

Cost for hydrogen highly depends on the production method chosen, with electrolysis typically implying the highest fuel costs compared to other production methods. This is also due to the fact that required electrolysers are still a costly technology, no matter if they are installed at bus depots or in centralized production facilities. Additional financial impacts arise from the need for large investments in own production facilities if hydrogen is produced on site (as today in Ruter's fuel cell bus project). As this method is the preferred option in Oslo/Akershus, higher hydrogen costs have to be encountered in general. Local H2 production costs then depend to a large extent on electricity prices to be paid by the plant operator and whether there is a potential to use cheap off-peak or spot price electricity generated from wind or solar energy. In combination with currently significantly increased fuel consumption of fuel cell buses in Oslo, fuel cell buses currently have significantly increased fuel costs.

3.6.5 Infrastructure costs

Biodiesel and bioethanol buses basically use the same infrastructure as conventional diesel buses with very low installation and operational/maintenance costs, thereby having only a limited impact on overall TCO. Biogas buses require dedicated infrastructure and additional safety measures as handling gas as fuel causes significantly higher investment in refueling infrastructure and also higher operational and maintenance costs. Standard hybrid vehicles use the same kind of infrastructure as conventional ICE buses of the same fuel type.

All types of electric or plug-in buses require charging infrastructure at bus depots. Associated costs significantly differ as different charging capacities are required for the different bus technologies because different battery capacities need to be charged over different timeframes. In general, overnight e-buses have the highest charging needs whereas plug-in hybrids have the lowest, implying different levels of complexity in charging infrastructure design and associated costs. As already stated, it is assumed that intelligent balancing of peak demand is required to balance electricity costs – therefore it needs to be assumed that more complex systems are required. Costs for individual charging solutions can therefore significantly differ depending on which kind of system is implemented. Additional costs for depot charging might be incurred if operators decide to have additional fast-charging facilities installed at depots as a backup charging opportunity. In general, there is currently a high level of uncertainty to be considered for such charging solutions as the market is not yet very developed and only few systems – especially to cater for larger numbers of buses – have been installed so far. Therefore, scale effects in general market volumes and for individual large-scale installations are only visible to a limited extent so far. A major additional investment need might arise at individual bus depots to ensure sufficient grid connection capacities – charging a large number of electric buses at an individual depot cause very high electricity needs which must to be catered for. Dependent on the local grid supply, significant costs for upgrading grid connections, installing new substations etc. might occur. If bus operators have their own workshops at bus depots, these also need to be upgraded if new technologies in general, but specifically all kinds of electric buses, are being introduced due to the specific technology used in these buses and the high voltage levels that need to be handled.

Buses using opportunity charging infrastructure even have increased incurring costs. In addition to depot charging installations, investment costs for

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[146] Source: Norwegian State Budget

installation of individual charging points both for inductive and conductive charging solutions are significant (about the same costs for each point as for a biodiesel refueling station catering 50 buses). Additional costs arise for local grid connection and associated civil works which can be significant, but highly depend on local conditions. Therefore it is important to reduce the total number of charging points installed in the entire network and to use them with a maximum number of buses to their largest possible capacity (e.g. at terminals). As such charging points need to be installed throughout public areas of the city, significant project management capacities are likely to be required to realize installations and ensure optimal distribution. Additional complications for installation might arise as buses recharging at individual points for a certain timeframe need to be able to park there – space is to be provided for this purpose.

Fuel cell buses have high infrastructure costs for refueling stations and potential hydrogen production facilities. Due to the limited number of installations so far, the lack of experience with large stations and the specific characteristics of hydrogen as a fuel, hydrogen refueling stations are even more expensive from an investment point of view than biogas stations, whereas operational and maintenance costs are comparable. High additional investment needs might occur when on-site production from electrolysis is chosen as production method; electrolysers at respective capacities cost today approximately the same amount as a hydrogen refueling station itself. For fuel cell buses additional costs typically arise as dedicated safety measures and workshop adaptions are required by regulation; depending on local conditions, these can be significant as well as the costs for associated project management.

3.6.6 Labor costs

Labor constitute up to 70% of overall TCO, and do not differ between the different powertrain technologies. Labor costs for bus drivers and cleaning and servicing of buses typically constitute the largest share of overall TCO and do not differ between technologies. It is assumed that approximately three bus drivers are needed for every bus in daily operations (excl. spare buses) to cater for operations in several shifts.

However, when introducing new technologies there is a potential need for additional buses and drivers from reduced passenger capacities and opportunity charging needs. Lower passenger capacities may drive more buses to transport the same amount of people. If these buses are either driven on routes with longer daily mileages required than such buses can deliver or have extended recharging/refueling needs that do not allow keeping the current timetable, a need for deployment of additional buses might arise. Although this also incurs additional costs for bus purchasing, maintenance and fuel, the main cost driver for such additional deployments is the labor cost of additionally required bus drivers. Therefore, such additional deployments are to be avoided by any mean as they can drive costs for service delivery on certain routes to an unjustifiable extent. In the current operational setup at Ruter, adding additional buses to the fleet is required for all buses using opportunity charging which has a significant impact on TCO.

3.6.7 Costs for downtime, reduced passenger capacity and opportunity charging needs

Reduced uptime/availability of buses with emerging technologies needs to be accounted for when assessing costs. Plug-in hybrid, electric and fuel cell buses will have significantly reduced availability rates especially in the first years of their deployment. This causes a need for having additional replacement buses at hand which deliver the public transport service required. These would not be required if only mature technologies at standard availability levels would be used for service delivery which justifies the consideration of these costs in overall cost assessments. Depending on the availability levels assumed (80-85% in first years of deployment) these costs can constitute up to 10% of overall TCO.

Reduced passenger capacity of electric and fuel cell buses cause additional costs. Due to the higher weight and volume of technology components on the buses, these vehicles have reduced passenger capacities which might cause problems in providing sufficient passenger transportation capacities. Due to this reason, additional buses might need to be added to the fleet in order to cater for reduced passenger transport capacities especially for larger fleets. This has the same overall cost effects as outlined above for the potential need to deploy additional buses because of reduced daily ranges and extended recharging/refueling needs. If these costs are added to overall TCO, this can have a significant impact: Depending on exact level of reduced passenger capacity, costs can increase by c. 5-20%. Due to improvements in battery and fuel cell technology and their associated weights, an increase in passenger capacity has been assumed for these vehicles so that the effect of reduced passenger capacity is reduced over time.

If buses need to be charged on the route by

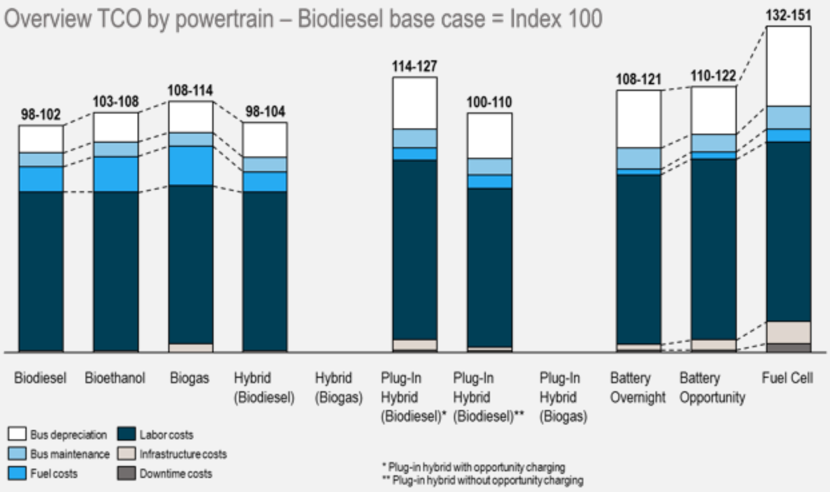


Figure 61: Illustration of typical TCO split for different technologies (12 meter bus), adjusted for reduced bus availability, reduced passenger capacity and additional buses needed due to opportunity charging needs in 2020

opportunity charging, more buses need to be added to the fleet, thus driving costs. In the current operational setup at Ruter with a high frequency schedule and no waiting times between two subsequent drive cycles of a bus, more buses need to be added to the fleet if deployed buses need to be recharged on the route. The required number of additionally needed buses has been analyzed based on selected routes in Ruter's area of operation where opportunity charging buses can be deployed (due to lengths of lines and available space at end points of lines for installation of recharging infra-structure). This additional share of more buses needed has then been factored in to the TCO calculations.

TCO

Figure 61 provides an overview on estimated Total Cost of Ownership (TCO) for solo buses deployed in 2020 over their ten year lifetime period. As of the data collected for this report, biogas hybrids and plug-in hybrids are not likely to be available until 2020, but rather from 2022/23 onwards only. TCO figures are indicated on an index base to directly illustrate the price premium for certain technologies compared to biodiesel buses as least costly option running on renewable fuel only. TCO have been calculated in a base case scenario (in this scenario, biodiesel is defined as index 100) as well as in a high and a low cost scenario which are reflected in the ranges indicated for each powertrain technology. High and low cost scenarios include variations in bus purchasing, maintenance, fuel, infrastructure and downtime costs on varying scales and where deemed applicable. Additional sensitivities such as reduced financing costs, increased annual mileage or increased bus lifetime have not been considered.

Fuel cell buses are expected to have the highest overall TCO, caused by significantly reduced passenger capacity, limited expected availability, still high vehicle purchasing costs and high required investments in refueling infrastructure including hydrogen production facilities by electrolysis. Battery overnight and opportunity buses have the second highest TCO, with a significant gap already to fuel cell buses. In their case, reduced passenger capacity and still significantly increased bus purchasing costs cause most of the price premium in TCO. Whereas in other studies, at least opportunity buses are expected to have lower TCO than conventional ICEs in the short to mid-term, this effect does not apply to Ruter due to the current operational setup which requires more buses to be added to the fleet. The same effect applies to plug.in hybrid buses operated with opportunity charging on the route which can have even higher TCO than opportunity battery buses, mainly driven by expected higher vehicle prices.

Of the conventional ICE technologies, biogas buses are expected to be the most costly option. The price premium for biogas buses is mainly caused by higher bus purchasing and infrastructure costs reflecting the technologically more complex handling of the gaseous fuel. In addition, fuel costs are higher than for bioethanol or biodiesel.

Biodiesel plug-in hybrid without opportunity charging as well as bioethanol buses range on a comparable TCO level with a limited price premium to biodiesel. Nevertheless, plug-in hybrid buses without opportunity charging can only be deployed on a limited number of lines as they

	Bus technology maturity level 2015	Commercial ready in 2020	Infrastructure maturity 2020	Fuel/energy availability in 2020	Reduced local emissions vs. Euro V diesel	Reduced WTW CO_2 emissions towards conventional diesel	Energy consumption	TCO Index 2020
Biodiesel	●	✓	●	✓	◕	◕	High	98-102
Bioethanol	◕	✓	●	(✓)[1]	◕	◕	High	103-108
Biogas	●	✓	●	(✓)[1]	◕	◕	High	108-114
HEV	◕	✓	●	✓	◕	◕	Medium	98-104
PHEV	◔	(✓)	◕	✓	◕	◕	Medium/low	114-127 [3]
Overnight	◔	(✓)	●	✓	●	●[2]	Low	108-121
Opportunity	◔	(✓)	◕	✓	●	●[2]	Low	110-122
Fuel cell	◔	(✓)	◕	(✓)[1]	●	●[2]	Medium	132-151

● High ○ Low ✓ Available (✓) Partly available

1) Capacity not sufficient for whole fleet 2) Renewable electricity, excluding CO2-impact from battery production which is significant 3) PHEV with opportunity charging

Figure 62: Summary of analysis results by technology towards 2020

need to be in the depot several times a day the get recharging and make sufficient use of their enhanced electric driving capabilities. This can be the case for buses which are used mainly in peak hour traffic, but this limits their potential to be driven on a comparable number of kilometers as other buses in the fleet with more operational flexibility; reduced annual mileage would also increase overall TCO for these buses.

Least costly powertrain options are expected to be conventional biodiesel as well as biodiesel hybrid solutions. If fuel prices stay at comparable levels as of today, also in relation to the other alternative fuels to be considered, these two powertrain options are expected to be most economic; higher bus purchasing costs for hybrid vehicles are almost completely offset by expected fuel savings.

4. Conclusions

This chapter concludes key areas from chapter 3 as well as presents a risk overview. See concluding overview of chapter 3 in figure 62.

In conclusion in 2020, a number of renewable powertrain options will be commercially ready. Infrastructure maturity differs somewhat, but will have improved significantly compared to 2015, as can be seen in figure below. In terms of total cost of ownership (TCO), PHEV and electric buses (overnight, opportunity and fuel cell buses) drive a significant price increase, and also improved environmental performance. Regarding total cost of ownership between different technologies, it is expected that the price premiums compared to biodiesel will diminish, whereas they can still be significant.

From a CO2 well-to-wheel emission standpoint, fully electric (both overnight and opportunity), PHEV biogas or biodiesel, fuel cells, and biogas EURO VI powertrains are more or less equivalent and all very good options. Replacing the current fleet with modern EURO VI biofuel buses will also have a dramatic effect on local emissions, albeit not to zero levels. It is important to keep in mind that a broad, immediate modernization of the bus fleet to the latest biofuel standard will have a bigger total environmental effect than a gradual introduction of a few electric buses. The choice of technology should therefore weigh a number of factors including costs, social benefits and environmental benefits. Some more details regarding pros and cons for various powertrains are presented in figure 63 and 64 page 20.

4.1 Main risks and uncertainties

The risk profiles of the different powertrain solutions are strongly correlated to the technological maturity. The ICE based powertrain is the most established solution with limited risks. Since maturing technologies such as overnight, opportunity and fuel cell buses have limited commercial testing and immature supply and service chains, these solutions are considered to have higher risk levels than other powertrain solutions. As for all maturing technologies, there is a risk that the technology never matures. A selection of key risks (not exhaustive) are presented in figure 65.

	Pros	Cons
ICE Biofuels - Biodiesel - Bioethanol - Biogas	> Bus technologies mature > Lowest purchase price > Low infrastructure impact > High route flexibility and range	> Renewability and CO2 emission of fuels needs to be managed > Highest emissions, noise > Low energy efficiency
Hybrids (HEV serial or parallel)	> Technology mature - in serial production > High range and route flexibility > No city infrastructure impact > Additional CO2 reduction > Up to 20% fuel savings	> Slightly more expensive than ICE biofuels on TCO basis, depending on fuel saves > More complex technology > Very limited electrical drive > Higher emissions, noise than pure electric > Lower energy savings than PHEV
Hybrids (PHEV serial or parallel)	> Up to 100% pure electric driving, depending on recharging frequency > Backup ICE lowers operational risk vs. fuel electric vehicles > High range and route flexibility > Lower emission & noise	> Technology under development > More complex powertrain vs. ICE biofuels or full electric > More batteries, weight, costs vs. HEV > City infrastructure charging required (conductive seems most developed) > Operational experience low

1) HEV = Hybrid Electric Vehicle. PHEV = Plug-in Hybrid Electric Vehicle

Figure 63: Pros and Cons by technology (1/2)

	Pros	Cons
Electric – Pure Overnight	> Zero tailpipe and potentially no CO2 emissions, depending on CO2 footprint of electricty > No city infrastructure required > High route flexibility > More mature than Opportunity EV and PHEV > Simple powertrain architecture	> High battery weight, uncertain battery lifetime, high cost impact > Reduced number of passengers > Reduced daily range of c. 240km > High bus purchasing costs > Mainly from producers new to European market
Electric – Opportunity - Conductive	> Zero emission potential > Less battery weight and costs vs. overnight > Larger range depending on recharging > Considered as future solution by most OEMS	> Higher investments due to city infrastructure > Less route flexibility > Shorter range without charging: c.20-40km
Electric – Opportunity - Inductive	> *Same as conductive* > Slightly more experience with infrastructure	> Infrastructure more complex to install > *Same as Conductive*
Electric – Fuel cells	> Zero emission potential > High route flexibility > Short refuelling times of about 10 mins > Larger daily ranges of 200-400km	> Technology not yet fully mature > Reduced no. of passengers > Lower energy efficiency > Expensive (bus and fuel production)

Figure 64: Pros and Cons by technology (2/2)

	ICE with biofuels	Hybrids	Fully electric	Fuel cell
Current Maturity	High	HEV: Medium High PHEV: Low/Medium	Low / Medium	Low
Key risks	Few risks as maturity is generally high Known issues in biogas supply chain Negative perception among public (based on uncertain sustainability	Lack of infrastructure standards (for PHEV) Bus battery performance lifetime shorter than expected Usage of hybrid electric buses might not be considered environmentally friendly as fully electric buses among the greater public, especially with regards to high penetration of electric passenger cars in Oslo	Lack of infrastructure standards Bus battery performance lifetime shorter than expected Electric buses have limited commercial testing and the risk for early phase implementation issues is high Varying uptime and service need of electric buses might impact total cost of ownership Aftermarket parts, competence	Lack of infrastructure standards Limited commercial testing and the risk for early phase implementation issues is high Varying uptime and service need of electric buses might impact total cost of ownership

Figure 65: Key risks

5. Assessment of battery bus implications for Ruter

This chapter includes answers of Ruter's five key questions regarding electric buses.

5.1 Best long-term solution

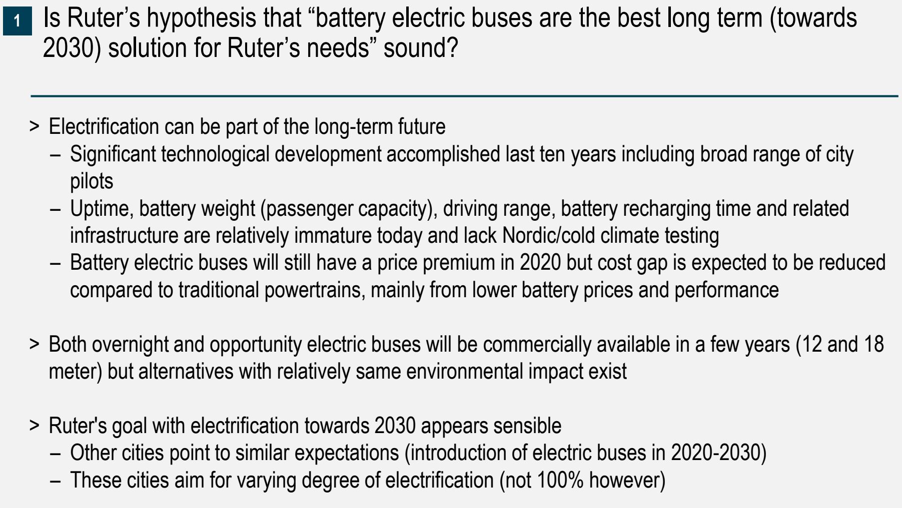
Is Ruter's hypothesis that "battery electric buses are the best long term (towards 2030) solution for Ruter's needs" sound? What are the main uncertainties? When will these buses and related infrastructure be (commercially) available for large scale deployment in our region, based on our actual needs?

Ruter needs to define what is the "best solution", as this needs to weigh a number of factors including economical costs, social benefits and environmental benefits. Scale of deployment is to a large extent driven by Ruter's appetite on a number of dimensions:

- Level of ambition in the definition of "renewable"
- Willingness to pay a premium for environmental gains
- Willingness to accept risks that may impact customers (potential increase in level of service disruptions from new technologies)
- Ruter's and potential operators' ability to deal with technological changes (organization, learning etc.)

The below should therefore be considered when determining "best":

- Different renewable energy powertrains have different environmental benefits. Electric buses, with zero tail-pipe emission and usage of green electricity, could provide very attractive CO2 benefits. However, from a CO2 well-to-wheel emission standpoint, fully electric (both overnight and opportunity), PHEV biogas or biodiesel, fuel cells, and biogas EURO VI powertrains are all very good options.
- As battery electric buses are still not fully mature, and cost for batteries are still high, total costs (TCO) over the lifetime of electric buses are up to c. 30% higher than biodiesel including bus costs, maintenance, infrastructure, fuel, labor etc. in 2020. In 2020, biodiesel (second generation) WTW CO2 emissions compared to fully electric is c.100-300% depending on fuel used and assumptions for battery production. When considering emissions from electric buses, it is key to understand that although battery electric buses may have zero emission locally, the battery production (often in China), tends to use significant amounts of energy, and depending on the energy mix used, may have 'high proportions of fossil energy and thereby CO2 emissions. This may mean that emissions in Oslo are very attractive, but overseas impact potentially less attractive. Other biofuels solutions, including hybrid electric, will be somewhere in between with regards to costs and WTW CO2 emissions, and could be attractive options.
- As with all new technologies, risks may go up, which could impact the customers' experience (timeliness of services, frequency of unplanned breakdowns etc.)? Technologies implemented should be sufficiently mature to minimize these risks. Today, there is very limited experience with operating a larger fleet of electric buses in



1 Is Ruter's hypothesis that "battery electric buses are the best long term (towards 2030) solution for Ruter's needs" sound?

> Electrification can be part of the long-term future
  – Significant technological development accomplished last ten years including broad range of city pilots
  – Uptime, battery weight (passenger capacity), driving range, battery recharging time and related infrastructure are relatively immature today and lack Nordic/cold climate testing
  – Battery electric buses will still have a price premium in 2020 but cost gap is expected to be reduced compared to traditional powertrains, mainly from lower battery prices and performance

> Both overnight and opportunity electric buses will be commercially available in a few years (12 and 18 meter) but alternatives with relatively same environmental impact exist

> Ruter's goal with electrification towards 2030 appears sensible
  – Other cities point to similar expectations (introduction of electric buses in 2020-2030)
  – These cities aim for varying degree of electrification (not 100% however)

Figure 66: Electrification as best long-term solution

Nordic climate. In addition, before large scale deployment can be introduced, a fully developed aftermarket (parts and service availability) needs to be established.
- Ruter needs to be able to handle the full cycle of new technologies (planning, tendering, follow-up and monitoring). Operators need to have sufficient time to be able to build knowledge to be able to respond to tenders with new technologies, and to operate buses with the new technologies. Too large changes too quickly could create significant disturbances. A potential mitigating factor is the timing of contracts, being spread out over time, thereby reducing the risks for a large step-change.

Key uncertainties are whether battery electric buses can improve sufficiently technically and economically given the inherent limitations in battery technology. The more battery electric buses can overcome the technical and economical limitations, the more they could be part of a long-term solution in Ruter's fleet towards 2030. Interviews and information provided from the market suggest that prices of batteries could improve by up to 5% per annum to 2025, and similarly performance could improve by up to 5% per annum. This means that the cumulative improvements could be large. This implies that battery electric buses will be a real contender towards 2030. However, long-term continuous developments are uncertain and may hit "ceilings". Price improvements are uncertain as they are dependent on broader developments in related areas (largely volumes in passenger cars).

Electric buses are expected to be commercially ready by 2020. Electric infrastructure, today largely lacking communication protocol standards, could be expected to be commercially available by 2020. See previous discussions in Chapter 3.
In summary, data and interviews suggest that electrification can be part of the long-term future. However, interviews and analyses also suggest that this does not imply that there only should be electric buses, as operating performance may still not be on par with biofuel ICEs or hybrid solutions. Bus electrification towards 2030 appears sensible. Similarly, interviews with other cities point to similar expectations:
- According to interview with trial in Utrecht, the Netherlands aim at running zero emission buses by 2025.
- Hamburg intends to purchase alternative powertrains for buses only from 2020 onwards and to establish an emission-free bus fleet in about 15-20 years (2030-2035) according to interviews

5.2 Challenges and cost drivers for infrastructure

What are the key challenges and cost drivers related to battery electric bus infrastructure?

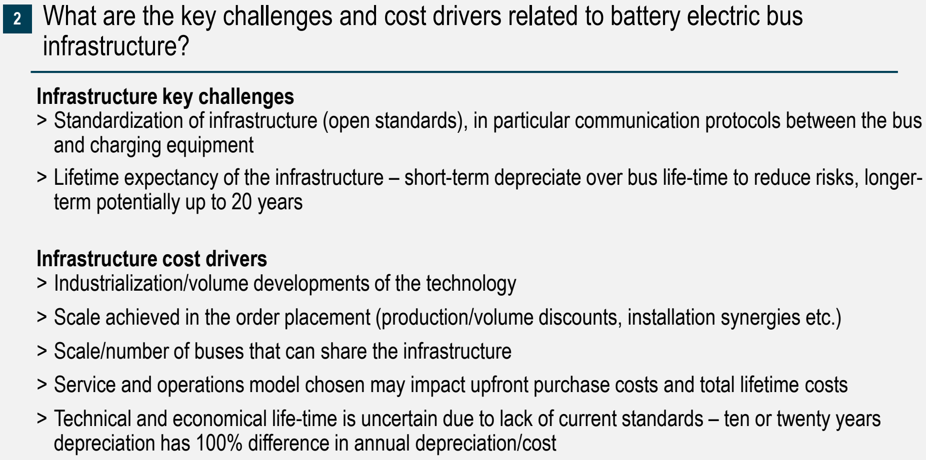
Although charging infrastructure represents significant investments, the costs are estimated to be smaller than the bus purchasing costs that will use the infrastructure. For detailed estimations and comments on costs, please refer to Chapter 3.

Challenges
- A key challenge is the standardization of infrastructure, in particular communication protocols between the bus and charging equipment
- Although standards may develop, they should be "open", to allow Ruter to benefit from a selection of providers and not be locked in to one solution
- Another challenge is the lifetime expectancy of the infrastructure – some interviews suggest the infrastructure should be depreciated over the lifetime of the bus or the contract, others suggest that 20 years or longer should be applied
  - In the short-term, depreciation over the life-time of the bus (or contract) is recommended to incorporate the risk that infrastructure may become obsolete after this point in time. There is also a risk that Ruter invests in the "wrong" standard.
  - Over a longer term, when infrastructure standards may be even more mature, a longer life-time and lower yearly depreciation could be sensible
  - Given the uncertainty, a middle approach seems appropriate to reflect that certain parts of the investments may be for the longer term (e.g. grid connections), whereas other parts may be shorter (the charging equipment, such as CCS-plug to the bus in the depot)

Figure 68

Cost drivers
- Costs for infrastructure will be driven by:
  -Technology chosen, and industrialization/volume developments of the technology
  -Scale achieved in the order (production/volume discounts, installation synergies etc.)
  - Scale/number of buses that can share the infrastructure
  - Service and operations model chosen may impact upfront purchase costs and total lifetime costs
  - Technical and economic life-time is uncertain due to lack of current standards – ten or twenty years depreciation has 100% difference in annual depreciation/cost.

- For opportunity charging, key cost drivers include:
  - Charging unit (pantograph or induction plate etc.)
  - AC/DC converters
  - Grid connections
  - Potential project management costs, e.g. city and infrastructure planning and labor for installation
  - At the depot, similar types of costs as for overnight charging is required
- Upgrade of grid connections could be needed to cater for power requirements
- Peak power requirements drive costs as electric utilities also charge for the peak power capacity
- For overnight charging, key cost drivers include
  - Grid connections
- Upgrade of grid connections could be needed to cater for power requirements
- Peak power requirements drive costs as electric utilities also charge for the peak power capacity
  - AC/DC converters
  - Charging unit (e.g. plug)
  - Potential project management costs, e.g. city and infrastructure planning and labor for installation



2 What are the key challenges and cost drivers related to battery electric bus infrastructure?

Infrastructure key challenges

> Standardization of infrastructure (open standards), in particular communication protocols between the bus and charging equipment

> Lifetime expectancy of the infrastructure – short-term depreciate over bus life-time to reduce risks, longer-term potentially up to 20 years

Infrastructure cost drivers

> Industrialization/volume developments of the technology

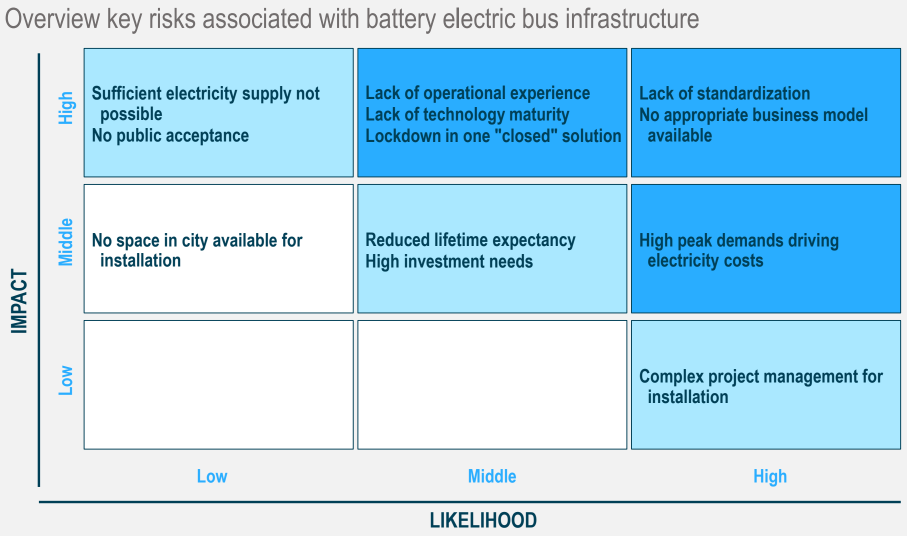
> Scale achieved in the order placement (production/volume discounts, installation synergies etc.)

> Scale/number of buses that can share the infrastructure

> Service and operations model chosen may impact upfront purchase costs and total lifetime costs

> Technical and economical life-time is uncertain due to lack of current standards – ten or twenty years depreciation has 100% difference in annual depreciation/cost

Figure 67: Challenges and cost drivers for infrastructure



Overview key risks associated with battery electric bus infrastructure

IMPACT \ LIKELIHOOD	Low	Middle	High
High	Sufficient electricity supply not possible No public acceptance	Lack of operational experience Lack of technology maturity Lockdown in one "closed" solution	Lack of standardization No appropriate business model available
Middle	No space in city available for installation	Reduced lifetime expectancy High investment needs	High peak demands driving electricity costs
Low			Complex project management for installation

Figure 68: Key risks associated with battery electric bus infrastructure

5.3 Potential impact on Ruter's business model and ownership structures

What are the most relevant business models, ownership models and responsibilities related to battery electric buses and infrastructure?

Battery electric buses will create a more complex eco-system compared to the current model. There are certain similarities to tram or trolley bus operations, where charging infrastructure is necessary.

There are a number of stakeholders in the ecosystem of electric buses:
- City (planning, traffic etc.)
- Public Transport Authority (PTA)
- Infrastructure operator
- Public Transport Operator (PTO)
- Bus manufacturer / service organization
- Infrastructure manufacturer
- Electric utility company

The electric bus ecosystem can be depicted as per Figure 69. First of all, there are different levels of city involvement. The PTA could be considered part of the city administration depending on location.

For the PTA, a key consideration is ownership and control over assets. To the largest extent possible to keep the current business model, Ruter should not own assets, but rather let the others own and operate assets. However, for strategically important assets, Ruter may seek to obtain ownership or right to control. This can be done in different ways (Ruter subsidiary, city utility, tram ownership etc.), which require further assessments of preconditions. Strategically important assets could be defined as:
- Asset is critical to execute Ruter's core business (tender bus services)
- Asset has synergies across operators
- Asset's nature is linked to the long-term business of Ruter
- Asset has a nature that is difficult to finance by the market based on parameters such as contract time, risk in residual values or outcome of standardization.

Electric charging infrastructure can broadly be divided into two areas: City charging infrastructure (relevant for opportunity charging) and depot charging infrastructure. City charging infrastructure would be placed at or near the bus stops. Currently, the bus stops are owned by the Environmental unit in the city. The required charging infrastructure with a longer economic horizon than a contract, should be owned/controlled by the public. The PTA / Ruter needs to take an active role in determining the approach to infrastructure in the city – this sets the playing field for electrification of bus operations. Outsourcing/third-party involvement with regards to infrastructure can be used to different degrees (e.g. construction, installation, service and maintenance, operations and control/monitoring). Opportunity charging infrastructure could potentially be owned or managed by the tram company – service/installation etc. can be outsourced. The infrastructure owner/operator should also be responsible for charging of power used by the different transport operators. The value chain of the infrastructure owner is shown in Figure 70, from provisioning of charging locations to billing for the services (power) provided.

As to the transport operators, they should be responsible for the bus investments and control fuel efficiency. They may also be responsible for the depot charging investments, operations and maintenance thereof. For depot investments, after the end of the contract, Ruter would assume control (similar to today).

The bus operators need to manage the bus OEMs as per today. For example, there may be different set-ups of service and maintenance (either inhouse or outsourced). With electrical powertrains, OEMs could potentially better execute some of the maintenance (at least short-term until operators have established sufficient inhouse capabilities).

The infrastructure OEMs similarly need to align closely with the infrastructure owner/operator, and could have different roles over the life-time (system design, installation, service and upgrades) depending on preferences of service model by the infrastructure owner/operator. The charging equipment producers also need to ensure compatibility vs. bus producers and also vs. the infrastructure owner/operator.

Other stakeholders, such as electric utility company providing power to the city infrastructure or depots, need to be closely involved in Ruter's overall plans to ensure electrification of bus services can happen. Interviews with other cities suggest that these adjacent stakeholders could be crucial in pilots and long-term implementation
- City planning needs to be involved to ensure charging locations can be established.
- Relevant authorities may have to establish new rules. For example, national energy authorities may have to decide on safety measures (e.g. height of the charging infrastructure).
- Road cleaning and maintenance may have views

on new infrastructure impacting accessibility around the bus stops.

For Ruter, the business model – tendering of services – may not change with introduction of electric buses. It appears however important to ensure that the playing field for operators are clearly defined to ensure commercial interest from the operators. Ruter needs to decide the technology for which the operators tender. Interviews with other cities suggest there is no best-practice set-up established as to how the ownership and tender specific questions shall be handled. Therefore, it is important that Ruter establishes its own strategy.

3 What are the most relevant business models, ownership models and responsibilities related to battery electric buses and infrastructure?

> Interviews with other cities suggest there is no best-practice set-up established as to how the ownership and tender specific questions shall be handled

> Many value chain stakeholders are willing to take on infrastructure ownership, e.g. infrastructure suppliers, grid/energy suppliers, bus suppliers

> Knowledge building in after-market and spare parts availability needs to be secured and uptime might be a key responsibility for the suppliers compared to today

> Business model might need to be more controlled and steered by Ruter during first wave of implementation versus today

> Limited number of stakeholders/owners in the value chain will be important to minimalize fingerpointing and to quickly gain learning by doing

> For strategically important assets (infrastructure), Ruter may seek to obtain ownership or right to control

Figure 69: Business and ownership models for e-bus infrastructure

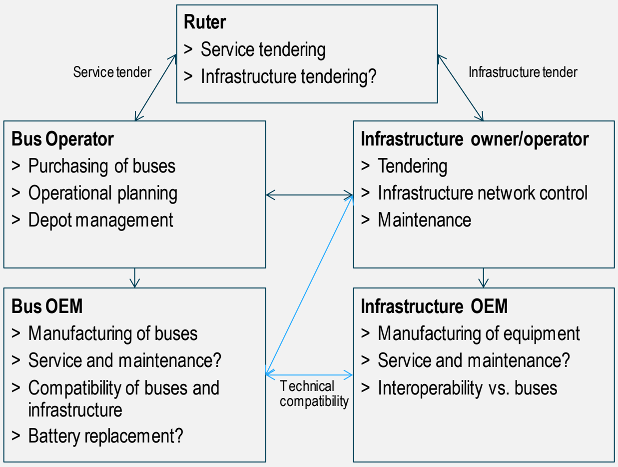


Figure 70: Overview of bus eco-system

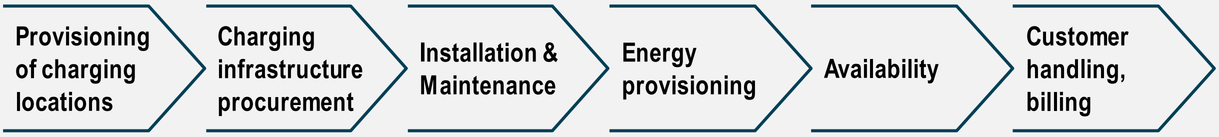


Figure 71: Infrastructure value chain [147]

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[147] Source: Interviews

5.4 Optimal approach towards 2020 target

What is the optimal approach towards the 2020 target, based on cost, quality and risk. (Strategic level). Consider dimensions such as:

- Low versus high pace of roll out of new technology?
- Should Ruter actively determine the bus technology mix or should it be left to the market?
- Extensive testing of buses and infrastructure – or direct commercial procurement?

Depending on risk and cost levels acceptable, the speed of implementation of electrification needs to be adjusted accordingly. As Ruter is carrying out its services via operators, it is key to keep a commercial perspective in all strategic considerations. When deciding to implement new technologies, the effects on contracts, suppliers, costs, revenues and passengers need to be fully assessed.

It is important that Ruter's ambitions, priorities etc are clearly communicated to the market. Ruter needs to set clear strategic directions, and via tenders steer to the desired technologies (by assigning criteria and weightings to fulfill objectives). However, Ruter should leave to the market to decide as much as possible regarding detailed bus specifics. Tendering of infrastructure should be separate from buses – the bus tender should specify infrastructure direction chosen by Ruter. The infrastructure solution needs to be clear when moving into the bus tender.

Based on interviews, it appears that the steps normally taken by PTAs when introducing electric buses are:

1. **Pre-commercial pilot (5-10 buses)**
2. **Small commercial tender (15+ buses)**
3. **Large commercial tenders.**

Firstly, there may be a need to acquire hands-on experience with electric buses in order to understand and verify the concept. In a lower risk scenario, an operational pilot may be needed, despite several already conducted and many pilots planned with electric buses across Europe. This should probably be some 5-10 buses to ensure some scale benefits (project management, infrastructure etc). The buses could potentially be phased in gradually to reduce risks. The main principle should be that the PTO (Ruter) acquires buses with the new technology if it is a smaller pilot. This has been the case in Helsinki and Gothenburg with a similar set-up to Ruter (the PTO is a tendering organization only and services executed by the PTOs). Experience from these cities suggest that pilots could either be part of the time-table (Helsinki) or run as extra service (Gothenburg). Another important element of a pilot would be to establish experience among the operators of electric buses. In Helsinki, the pilot is designed to involve four to five operators. These will thereby build internal capabilities of electric buses, and also have a level playing field when tendering for electric bus contracts.

Secondly, a smaller commercial tender could be introduced directly. The tender should cover a number of routes, for which electrification (partly or fully) could be realistic. As to the buses, the optimizations should be left to the market to decide. The outcome could be hybrid plug-ins as a first step towards fully electric buses, or fully electric buses if deemed mature enough by operators (with help from bus producers). The bus tender and evaluation need to promote lower energy consumption/higher fuel efficiency and also environmental footprint and CO2 reduction, in order to promote electrification.

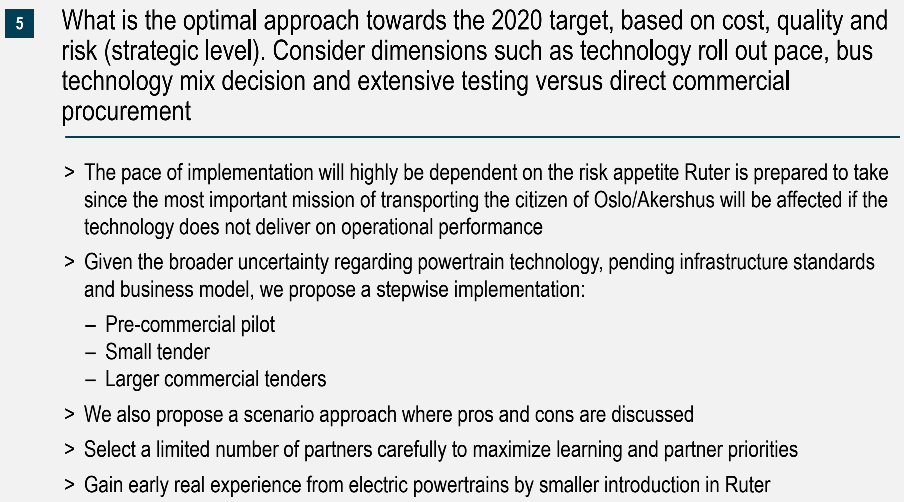
Thirdly, after the smaller commercial tender, larger tenders could be introduced with stronger commercial focus.

As to choice of infrastructure, this should ideally support different types of electric bus generations (PHEV, full EVs). As to the economic assessment, infrastructure should potentially assume full depreciation in line with economic life of first technology, as infrastructure technology may change/develop over time.

How Ruter introduces electric buses can be either in existing contracts or at the end of contracts. Experience and interviews suggest that it could be more costly to introduce a new technology in an existing contract. The operator in the existing contract has potentially incentives to maximize payment, without risk losing the contract to a competitor. The benefit of introducing a new technology in an existing contract could be that new technologies could be introduced faster.

Final recommendations going forward to realize the 2020 targets established for Ruter:

- Continued close dialog with the supplier industry, operators and other public authorities is required to monitor developments
- Gain real experience soon from electric powertrain by smaller introduction in Ruter, and thereafter continued with gradual increases
- Ensure that total long-term environmental impact is prioritized
  - A large deployment of the "second best"



5

What is the optimal approach towards the 2020 target, based on cost, quality and risk (strategic level). Consider dimensions such as technology roll out pace, bus technology mix decision and extensive testing versus direct commercial procurement

- The pace of implementation will highly be dependent on the risk appetite Ruter is prepared to take since the most important mission of transporting the citizen of Oslo/Akershus will be affected if the technology does not deliver on operational performance
- Given the broader uncertainty regarding powertrain technology, pending infrastructure standards and business model, we propose a stepwise implementation:
  - Pre-commercial pilot
  - Small tender
  - Larger commercial tenders
- We also propose a scenario approach where pros and cons are discussed
- Select a limited number of partners carefully to maximize learning and partner priorities
- Gain early real experience from electric powertrains by smaller introduction in Ruter

Figure 72: Optimal approach towards the 2020 target

renewable option may be the most cost and
environmentally effective solution
- A small scale deployment of the "best"
solution may have lower overall impact

Annex – Sources

Interviews

Bus manufacturers:
- BYD
- Ebusco
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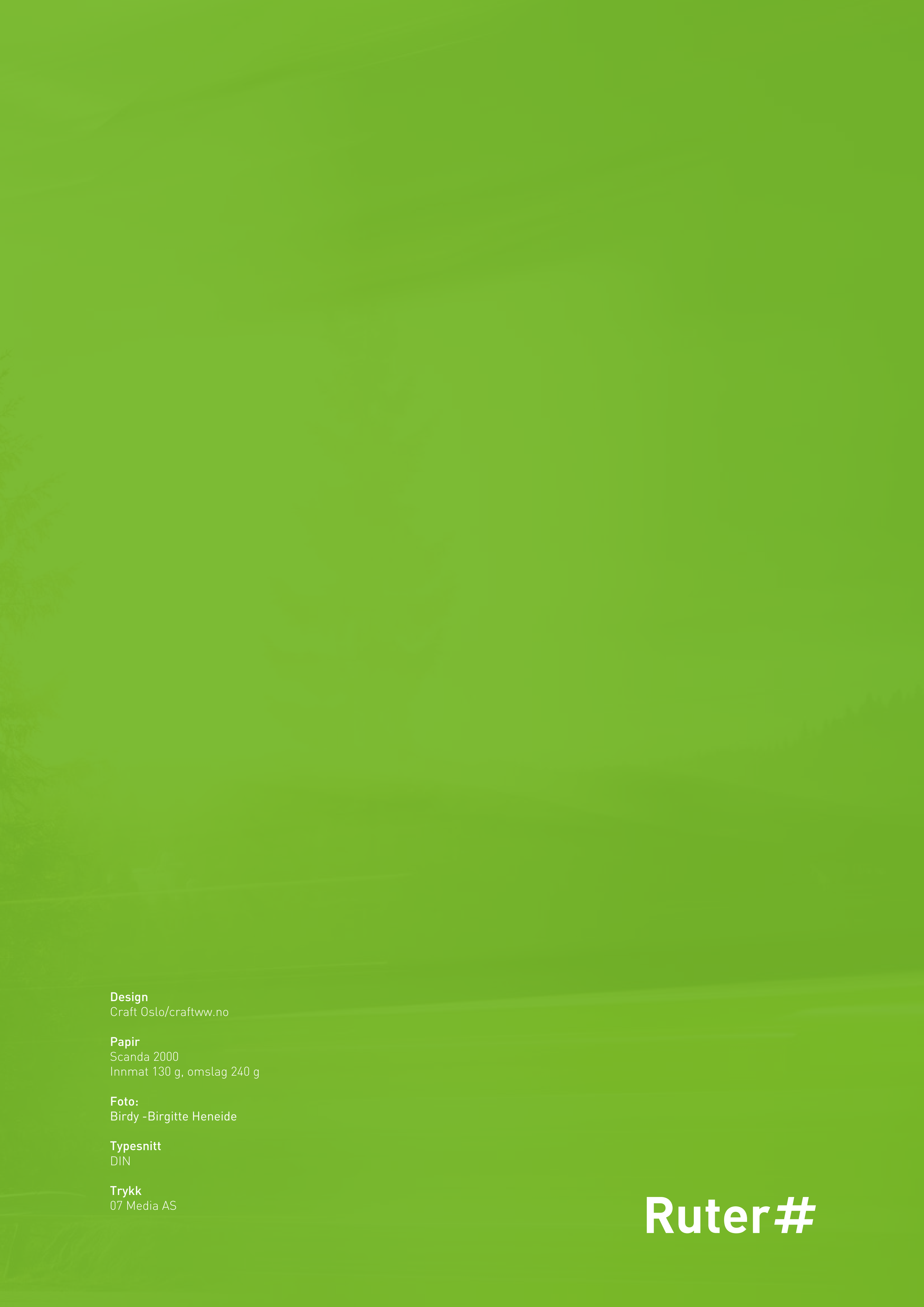

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