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TECHNOLOGY COLLABORATION PROGRAMME

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IEA HEV Task 33 – Battery Electric Buses

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Summary

Bus transportation systems using battery electric buses are reaching increasing attention in recent years. After several years of testing battery electric buses in demonstration projects, now several cities and urban bus operators started to electrify their bus fleets partially/completely. Recent developments show that new charging strategies and advanced energy storage technologies enable full-day operation of battery electric buses. The objective of the IEA HEV Task 33 "Battery Electric Buses" (2018 – 2020) is to analyse and assess the current state of technology and demonstration experiences of battery electric buses to conclude on future perspectives. The following partners cooperate in Task 33: Spain: IREC – Catalonia Institute for Energy Research, Canada: NRCAN – Natural Resources Canada, Office of Energy Research and Innovation, Finland: VTT, Germany: hySOLUTION, South Korea: Ulsam University, and Austria: JOANNEUM RESEARCH (Operating Agent). Beside the participating countries further cooperations were established: IEA AMF Annex 53 „Sustainable Bus Systems", (Molina Center for Energy and the Environment, Chile) and PRO-EME: Promoting Electric Mobility in Urban Europe, a project in the program ERA-NET Electric Mobility Europe, (DLR, Germany).

The organization of workshops with participation from industry, research organizations, technology policy experts and governmental institutions established an international basis for the exchange of information on the relevant issues on e-buses. Two workshops on state of technology and future perspectives of battery electric buses in Helsinki 2018 and Eindhoven 2019 were organised.

The results are the following key issues for battery electric buses:

- Key drivers: climate protection and decarbonisation of the transportation sector, improvement of air quality, the European Green Vehicle Directive,
- Technological aspects: battery electric buses and adequate charging systems for depot or opportunity charging on the road are available on the market,
- Experiences from demonstration projects:
  - Paradigm shift from vehicle procurement to system procurement,
  - Early stakeholder involvement in the planning and joint feasibility study necessary,
  - IT supporting fleet monitoring to optimise operation,
  - Integrating e-bus services into the overall city transport decarbonisation/defossilisation strategy,
- Rolling out of battery electric bus fleets in the Netherlands: Amsterdam and Eindhoven have the most innovative and biggest e-bus fleet in Europe,
- Performance indicators: operating costs, energy consumption, charging and overall system performance,
- Environmental aspects: life cycle assessment necessary to determine environmental impacts. Battery electric buses are most energy efficient bus system and the use of additional renewable electricity maximizes the environmental benefits,
- Economic aspects: In the baseline situation the total costs of the different bus systems are:
  - E-bus system with
    - depot charging 1.2 €/km,
    - opportunity charging 1.0 €/km,
  - Hydrogen bus system using renewable hydrogen from electrolysis 1.9 €/km,
  - Diesel bus system 0.9 €/km,
- R&D issues: fleet management, heating and cooling systems and strategies, inductive charging at stations/road, high power charging 1 MW and higher, light weight vehicles,
- Dissemination: several dissemination activities were undertaken, and
- Outlook: the expectation is *"that 2020 – 2030 will be the century of battery electric buses in urban environment"*.

Zusammenfassung

Bussysteme mit batterie-elektrischen Bussen haben in den letzten Jahren zunehmende Bedeutung erlangt. Nach umfangreichen weltweiten Demonstrationsprojekten sind die elektrischen Bussysteme technologisch soweit entwickelt, um im täglichen Betrieb eingesetzt werden zu können. Die IEA HEV Task 33 "Battery Electric Buses" (2016 – 2020) hat zum Ziel, den gegenwärtigen Entwicklungsstand von Transportsystemen mit batterie-elektrischen Bussen zu untersuchen und zu bewerten, um daraus Zukunftsperspektiven für den breiten Einsatz von batterie-elektrischen Busflotten zu erarbeiten. Die folgenden Partner arbeiten in Task 33 zusammen:

Spanien: IREC – Catalonia Institute for Energy Research, Canada: NRCAN – Natural Resources Canada, Office of Energy Research and Innovation, Finland: VTT, Germany: hySOLUTION, Südkorea: Ulsam University und Österreich: JOANNEUM RESEARCH (Operating Agent). Neben diesen Partnerländern gibt es auch eine Kooperation mit der IEA AMF Annex 53 „Sustainable Bus Systems", (Molina Center for Energy and the Environment, Chile) und PRO-EME: Promoting Electric Mobility in Urban Europe, ein ERA-NET Electric Mobility Europe Projekt, (DLR, Germany).

Zwei Workshops mit internationalen Teilnehmern aus der Industrie, der Forschung, der Technologiepolitik und der öffentlichen Verwaltung waren die Basis für den Erfahrungsaustausch und den Analysen. Die Workshops fanden zum Stand der Technik in Helsinki 2018 und zu den zukünftigen Perspektiven von batterie-elektrischen Bussen in Eindhoven 2019 statt.

Die Ergebnisse zu den Schlüsselthemen von batterie-elektrischen Bussen sind:

- Motivationen: Klimaschutz, Dekarbonisierung des Transportsektors, Verbesserung der Luftqualität und die europäische Direktive „Green Vehicle Directive",
- Technologische Aspekte: batterie-elektrische Busse und entsprechende Ladesysteme im Busdepot und auf der Strecke sind am Markt erhältlich,
- Erfahrungen aus den Demonstrationsprojekten:
    - Paradigmenwechsel vom bisherigen Buskauf zu einem Gesamt-Bussystem ist notwendig,
    - Frühe Stakeholder-Einbindung in die Planung und Machbarkeitsanalysen ist wesentlich,
    - IT-Unterstützung im Flottenmonitoring ist Voraussetzung für optimalen Betrieb,
    - Integration von Transportdienstleistungen mit E-Bussen in städtische Nachhaltigkeitsstrategien,
- Roll-out von batterie-elektrischen Busflotten in den Niederlanden: Amsterdam und Eindhoven haben derzeit die innovativsten und größten E-Busflotten in Europa,
- Betriebsindikatoren: Betriebskosten, Strombedarf, Parameter zur Ladeinfrastruktur und Gesamtsystem,
- Umweltaspekte: Lebenszyklusanalyse als Voraussetzung zur Umweltbewertung zeigt, dass batterie-elektrische Busse die höchste Energieeffizienz haben und zusätzlicher erneuerbarer Strom die Umweltvorteile maximiert,
- Ökonomische Aspekte: Im Basisfall sind die Gesamtkosten der Bussysteme folgende:
    - E-Bussystem mit
        - Depotladung 1.2 €/km,
        - Streckenladung 1.0 €/km,
    - Brennstoffzellen-Bus mit erneuerbarem Wasserstoff 1.9 €/km,
    - Dieselbus 0.9 €/km,
- Forschungsbedarf: Flottenmanagement, Heiz- und Kühlsysteme, induktive Ladesysteme bei den Stationen bzw. auf der Straße, Schnellladung mit 1 MW und Leichtbaufahrzeuge,
- Zahlreiche Informationsaktivitäten wurden durchgeführt, und
- Ausblick: Es besteht die Erwartung, dass „2020 – 2030 das Jahrzehnt der batterie-elektrischen Busse im städtischen Umfeld wird".

1 Aim of the activity

This chapter covers the motivation, the goal and scope, the approach and the cooperations and partners

1.1 Motivation

1.1.1 Developing and testing of battery electric buses

Bus transportation systems using battery electric buses are reaching increasing attention in recent years. After several years of testing battery electric buses in demonstration projects, now several cities and urban bus operators started to electrify their bus fleets partially/completely. Recent developments show that new charging strategies and advanced energy storage technologies enable full-day operation of battery electric buses, e.g. using the opportunity of fast charging concepts. Significant cost reductions are reached and further expected due to technology standardization and economy of scale. More than 20 bus producing companies in Europe already offer various types of battery electric buses. Main bus companies started battery electric buses in serial production, because battery electric bus systems have the potential to substitute diesel buses in cities soon.

Numerous of innovative projects were initiated in recent years, especially in central European countries, e.g. from pilot projects towards commercial use (e.g. Geneva, Amsterdam – Figure 1, Helsinki). They tested and demonstrated various types of battery electric buses, charging methods and strategies as well as energy storage systems. Based on the daily collection of experiences in operating battery electric buses an evaluation and analysis of key aspects from worldwide electric bus projects (e.g. charging strategies, electric energy storage systems) is ongoing. Urban public transport is the promising starting sector for the implementation of battery electric buses also be realizing synergies to already existing electric infrastructure, e.g. tram, metro.

Figure 1: Battery electric buses at charging station in Schiphol Airport

The facts on battery electric buses globally are the following (IEA, Global EV Outlook 2019):

- Global stock of battery electric buses increased by 25% in 2018 relative to 2017, reaching about 460,000 vehicles,
- In 2018, over 92,000 new battery electric buses were registered, from 104,000 in 2017,
- China accounts for 99% of the global market for battery electric buses, and
- Outside of China:
    - about 900 battery electric buses were registered in 2018, mostly in Europe,
    - Latin America had its first roll out with 200 battery electric buses in Chile and 40 in Ecuador, and
    - more than 300 battery electric buses in the United States.

1.1.2 Clean Vehicles Directive

In Europe the Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles[1] now pushes the market introduction of clean vehicles significantly. The "Clean Vehicles Directive" promotes clean mobility solutions in public procurement tenders, providing a solid boost to the demand and further deployment of low- and zero-emission vehicles. This Directive defines "clean vehicles" and sets national targets for their public procurement. It applies to different means of public procurement, including purchase, lease, rent and relevant services contracts. The Directive needs to be transposed into national law in EU member countries by 2 August 2021.[2]

The Directive defines a "clean vehicle" as follows:

- Clean light-duty vehicle: any car or van meeting the following emission thresholds:
    - until 31 December 2025: no more than 50 g/km CO_2 and up to 80% of applicable real driving emission (RDE) limits for NOx and PM;
    - from 1 January 2026: only zero-emission vehicles.
- Clean heavy-duty vehicle: any truck or bus using one of the following alternative fuels: hydrogen, battery electric (including plug-in hybrids), natural gas (both CNG and LNG, including biomethane), liquid biofuels, synthetic and paraffinic fuels, LPG.[2]

The Directive also sets a separate definition for "zero-emission heavy-duty vehicles" (clean vehicle without an internal combustion engine, or with an internal combustion engine that emits less than 1 g CO_2/kWh), as a sub-category of clean heavy-duty vehicles.

[1] Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles, https://eur-lex.europa.eu/eli/dir/2019/1161/oj

[2] European Commission, 2019: Clean transport, Urban transport - Clean Vehicles Directive, https://ec.europa.eu/transport/themes/urban/clean-vehicles-directive_en

The Directive sets out mandatory minimum procurement targets in each Member State as national targets for clean light-duty vehicles, trucks and buses. On buses, 50% of the minimum target for the share of clean buses has to be fulfilled by procuring zero-emission buses. The national targets are set for for buses:

- 2021 -2025 between 24 – 45%, and
- 2026 – 2030 between 33 – 65%.

1.2 Goal and scope

The objective of the Task 33 (2016 – 2020, Figure 2) is to analyse and assess the current state of technology and demonstration experiences of battery electric buses towards a broad market roll out. This covers on one hand the bus technology, e.g. battery or capacitor system, and on the other hand the charging infrastructure, e.g. fast charging stations at the bus stop and its optimal integration in an urban infrastructure, e.g. synergies with trams, metro or trolley bus systems. The task work is done based on an analysis of ongoing demonstration projects and the starting roll out phase of battery electric buses worldwide. Based on this the future perspectives and challenges for battery electric buses are analysed and described. This includes the identification of major challenges e.g. technology, costs, public acceptance and the necessary R&D demand. Finally, the key aspects for a successful broad introduction of battery electric buses and the necessary framework conditions are concluded.

The work is done in a close cooperation of the relevant stakeholders from the three focus groups:

- Provider of public transportation services,
- System and technology provider, and
- Research institutions.

The results are continuously documented and disseminated via e.g. presentations, workshops, conference contributions, and publications.

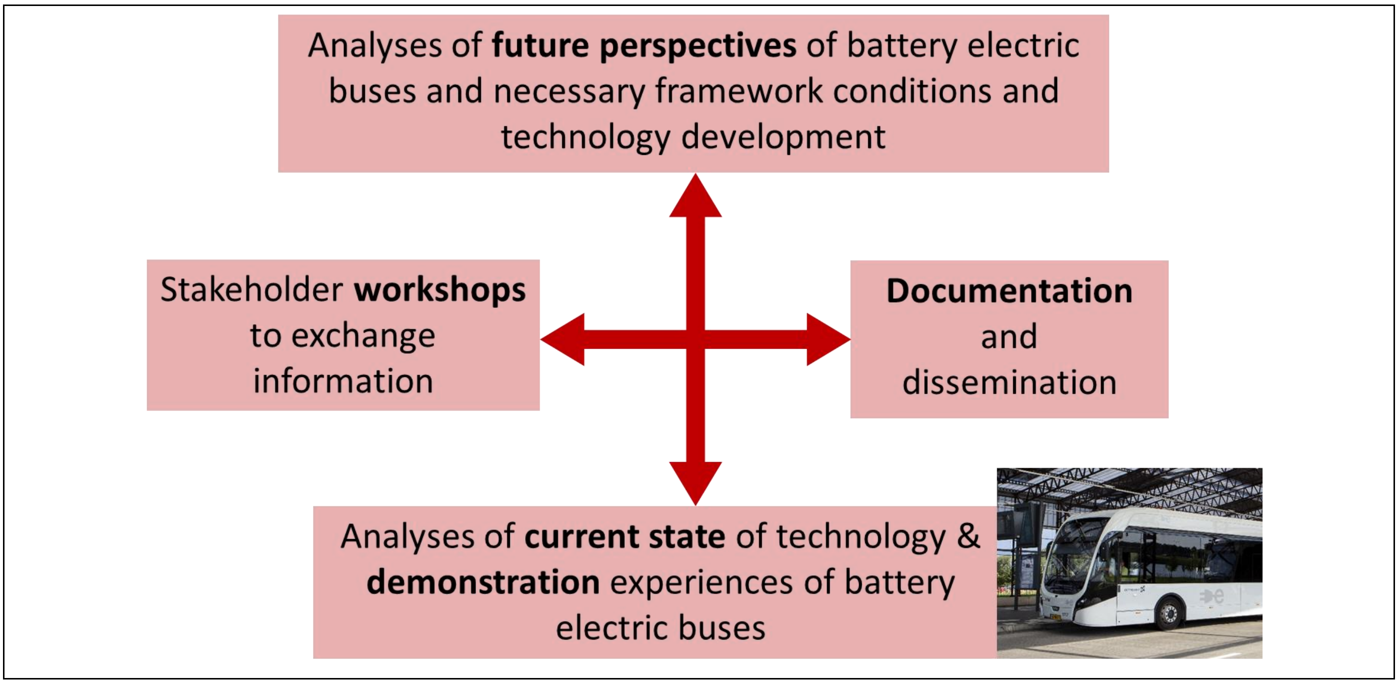


Figure 2: Objectives of Task 33

The major activities are:

- Identify and analyse state of technology and systems of battery electric buses,
- Collect and document „International Success Stories“ in a common format,
- Give overview of systems and technology providers with characteristic data,
- Stakeholder involvement in workshops in combination with site visit,
- Analyse combination of trolley and battery bus systems,
- Integration and use of existing infrastructure of trams, trolleys and metro,
- Identify success factors, e.g. size of bus, distances between bus stops,
- Describe and define various loading strategies,
- Analyse sustainability issues – economic, environmental and social aspects,
- Identify R&D demand,
- Conclude and summarize future perspectives, and
- Presentations and contributions at conferences.

1.3 Approach

The most important activity of the working method (Figure 3) is the organization of expert workshops in different member countries to involve the stakeholders in the value chain of battery electric buses, e.g. provider of public transportation services, system and technology provider, research institutions. The organization of workshops with participation from industry, research organizations, technology policy experts and governmental institutions provides an international basis for the exchange of information on the relevant activities. The focus of the expert workshops is to analyse, discuss and document the

- State of technology for battery electric buses, and
- Future perspectives of battery electric buses.

The workshops are combined with site visits to ongoing demonstration activities of battery electric buses in daily life application.

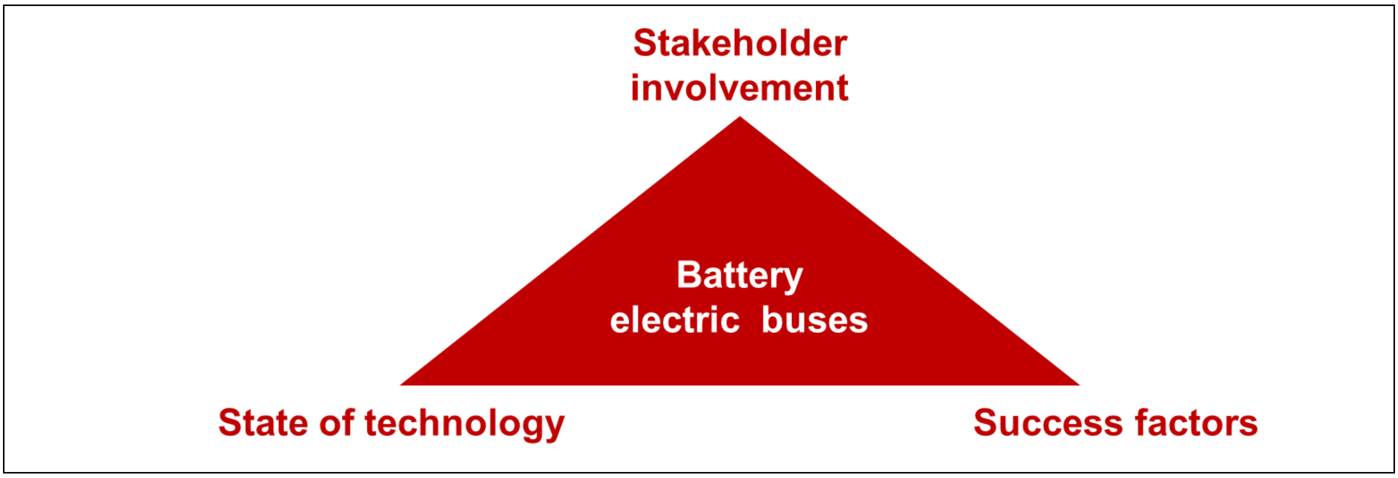


Figure 3: Working method

1.4 Cooperations and partners

1.4.1 IEA HEV TCP

The Technology Collaboration Programme on Hybrid and Electric Vehicles (HEV TCP) was previously known as the Implementing Agreement for co-operation on Hybrid and Electric Vehicle Technologies and Programmes (IA-HEV). The labelling changed in 2016. (see www.ieahev.org)

Vision

In November 2014, the IEA Committee on Energy Research and Technology (CERT) approved the fifth phase of operation for HEV TCP, which is scheduled to run from 1 March 2015 until 29 February 2020.

Mission

The HEV TCP ExCo considers policy/decision makers in governmental bodies at national, regional and city levels, in the automotive industry, its component suppliers and in utilities as the target audience for its work. These include the HEV TCP Contracting Parties, which are representing national governments. The HEV TCP mission is to supply this target audience with objective information to support decision making, to function as a facilitator for international collaboration in pre-competitive research and demonstration projects, to foster international exchange of information and experiences, and sometimes to function as a promoter for Research, Development, Demonstration and Deployment (RDD&D) projects and programmes.

Strategic Objectives for Phase 5 (2015−2020)

- To produce and disseminate objective information - for policy and decision makers - on hybrid and electric vehicle technology, projects and programmes, and their effects on energy efficiency and the environment. This is done by means of general studies, assessments, demonstrations, comparative evaluations of various options of application, market studies, technology evaluations, highlighting industrial opportunities, and so forth.
- To be a platform for reliable information on hybrid and electric vehicles.
- To collaborate on pre-competitive research projects and related topics and to investigate the need for further research in promising areas.
- To collaborate with other transportation related IEA Technology Collaboration Programmes, and to collaborate with specific groups or committees with an interest in transportation, vehicles and fuels.

Members

The 19 member countries of IEA HEV TCP are:

1. Austria,
2. Belgium,
3. Canada,
4. Denmark,
5. Finland,
6. France,
7. Germany,
8. Ireland,
9. Italy,
10. the Netherlands,
11. Norway
12. Portugal,
13. Republic of Korea,
14. Spain,
15. Sweden,
16. Switzerland,
17. Turkey,
18. United Kingdom, and
19. United States of America.

Phase 4&5 (2009–2020) Tasks

The tasks are:

- Task 1: EV Information Exchange,
- Task 10: Electrochemical System,
- Task 21: Accelerated ageing testing for lithium-ion batteries - concluded in 2017,
- Task 23: Light electric vehicle parking and charging infrastructure,

- Task 24: Economic impact assessment of e-mobility,
- Task 25: Plug-in Electric Vehicles - concluded in 2017,
- Task 26: Wireless power transfer for electric vehicles - concluded in 2019,
- Task 27: Electrification of transport logistic vehicles - concluded in 2017,
- Task 28: Home grids and V2X technologies - concluded in 2018,
- Task 30: Assessment of environmental effects of electric vehicles,
- Task 31: Fuels and energy carriers for transport - concluded in 2017,
- Task 32: Small Electric Vehicles,
- Task 33: Battery Electric Buses - concluded in 2020,
- Task 34: Batteries,
- Task 35: Fuel Cell Electric Vehicles,
- Task 36: EV consumer adoption and use,
- Task 37: Extreme Fast Charging,
- Task 38: Marine Applications (e-Ships),
- Task 39: Interoperability of e-Mobility Services,
- Task 40: CRM4EV - Critical Raw Material for Electric Vehicles,
- Task 41: Electric Freight Vehicles
- Task 42: Scaling Up EV Markets and EV City Casebook,
- Task 43: Vehicle/Grid Integration, and
- Task 44: Impact of Connectivity and Automation on Electrified Vehicle Usage and Benefits.

1.4.2 Partners in Task 33

The following partners in 6 countries cooperate in Task 33 with their own financing (Figure 4):

- Spain: IREC – Catalonia Institute for Energy Research,
- Canada: NRCAN – Natural Resources Canada, Office of Energy Research and Innovation,
- Finland: VTT,
- Germany: hySOLUTION,
- South Korea: Ulsam University, and
- Austria: JOANNEUM RESEARCH.

Figure 4: Countries and institutions in Task 33

1.4.3 International cooperations

Beside the participating countries also the following cooperations were established:

- IEA AMF Annex 53 „Sustainable Bus Systems“, Gianni Lopez (Molina Centre for Energy and the Environment, Chile), and
- PRO-EME: Promoting Electric Mobility in Urban Europe, a project in the program ERA-NET Electric Mobility Europe (EME), Stephan Schmid (DLR, Germany).

1.4.4 Work sharing in Task 33

The work sharing in Task 33 was the following:

- Task management and operating agent (JOANNEUM RESEARCH),
- Overall bus&charging technologies&system (VTT, JOANNEUM RESEARCH),
- Lessons learnt from demonstration projects (VTT, IREC, JOANNEUM RESEARCH),
- Market aspects: charging system and bus providers (JOANNEUM RESEARCH, proEME/DLR),
- Economic aspects (JOANNEUM RESEARCH, VTT and proEME/DLR),
- Environmental aspects (JOANNEUM RESEARCH),
- Comparison to hydrogen fuel cell buses (JOANNEUM RESEARCH, hySOLUTION),
- Business models and procurement procedure (JOANNEUM RESEARCH, IREC),
- R&D demand (JOANNEUM RESEARCH, Ulsam University),
- Upscaling to large fleets e.g. electric grid connection (JOANNEUM RESEARCH, VTT), and
- Summarizing key issues (JOANNEUM RESEARCH, VTT).

1.4.5 National Project Advisory Board

A National Project Advisory Board was initiated by the funding agencies (FFG and Climate and Energy Fund) and established in 2018. The National Project Advisory Board had one meeting in 2018, 2019 and 2020 during the working period of Task 33.

The activities of the National Project Advisory Board are the following mainly motivated to stimulate the information exchange in Austria:

- The operating agent informs on the actual activities and results (e.g. highlights) on the international level and the Austrian contributions,
- Strategic accompaniment, professional consultation and support on transferring the task activities and (interim) results, and
- Information exchange on the Austrian actives in the TCP HEV – Hybrid and Electric Vehicle, AMF – Alternative Motor Fuels and AFC – Advanced Fuel cells.

The members of the National Project Advisory Board were:

- KLIEN: Gernot Wörther,
- FFG: Maria Bürgermeister-Mähr,
- BMK: Andreas Dorda, Constanze Kiener, Reiner Reinbrech,
- AustriaTech: Walter Mauritsch,
- JOANNEUM RESEARCH: Gerfried Jungmeier, Martin Beermann,
- BEST - Bioenergy and Sustainable Technologies: Dina Bachovsky, Andrea Sonnleitner, and
- HyCentA – Hydrogen Center Austria: Alexander Trattner.

The following IEA tasks/annexes of the TCPs were represented by these members:

- HEV:
  - Task 30 „Environmental Effects of Electric Vehicles” (G. Jungmeier)
  - Task 33 „Battery Electric Buses“ (G. Jungmeier)
  - Task 40 “CRM4EV Critical Raw Material for Electric Vehicles” (M. Beermann)
- AMF - Annex 59 „Lessons Learnt“ (A. Sonnleitner)
- AFC - Annex 34 “Transport Applications“ (A. Trattner)

The National Project Advisory Board initiated the Austrian Expert Workshop “Future of Battery Electric Buses in Austria” that was held on October 8, 2019 in Graz, Austria. This Austrian Expert Workshop was organised by JOANNEUM RESEARCH in cooperation with the Climate and Energy Fund and the BMK.

2 Results

After an overview of the results, the detailed results are described.

2.1 Overview

The results are structured the following:

- Expert workshops on battery electric buses,
- Key drivers for battery electric buses,
- Technological aspects,
- Experiences from demonstration projects,
- Rolling out of battery electric bus fleets in the Netherlands,
- Fleet management,
- Performance indicators,
- Environmental aspects,
- Economic aspects,
- Comparison to other low- or zero-emission bus systems,
- Dissemination, and
- Outlook.

2.2 Expert workshops on battery electric buses

2.2.1 Expert workshop on current status

The Task 33 workshop "Battery Electric Buses – State of Technologies and Practical Experiences" took place in Helsinki/Finland on December 11&12, 2018.

The aim of the expert workshop of Task 33 was to analyse, discuss and assess the current state of technology of battery electric bus systems.

The main topics for the workshop were:

1. Charging technologies and strategies,
2. Bus technologies,
3. Environmental and economic assessment, and
4. Experiences around the globe.

To gain conclusion in group work on:

1. State of technology for battery electric buses,
2. State of technology for charging technologies and concepts, and
3. Identification of key aspects for battery electric bus systems.

The workshop was structured in the following sessions:

1. Keynote,
2. Experiences in Europe, Asia and America,
3. Assessment,
4. Group work,
5. Visit of Helsinki battery bus system.

The format of the workshop was based on presentations, discussion and group work.

The main results of the workshop are covering the following issues, which are described in detail in the following chapters:

- European projects,
- Current experiences,
- Lessons learnt from demonstration,
- Main charging strategies,
- Manufacturers of battery electric buses,
- Interoperability,
- Heating and cooling,
- Key performance indicators,
- Additional indicators,
- Hydrogen fuel cell bus,
- Environmental effects,
- Economic effects,
- Main challenges for battery electric buses,
- Strategy to have zero-emission public transport,
- Rolling out phase,
- Pilot cities for rolling out battery electric buses, and
- Case city "Eindhoven".

The documentation of the workshop is in Annex 4.1.

2.2.2 Expert workshop on future perspectives

The expert workshop "Future Perspectives of Battery Electric Buses" took place in Amsterdam and Eindhoven (NL) in autumn 2019. The aim of the expert workshop of Task 33 was to analyse, discuss and assess the future perspectives for battery electric bus systems in an urban environment.

The main topics of the workshop were:

1. Charging technologies and strategies,
2. Bus technologies,
3. Environmental and economic assessment,
4. Experiences around the globe,
5. Framework conditions,

6. Main challenges and open issues e.g. R&D demand, and
7. Site visits of battery electric buses in daily operation in Amsterdam and Eindhoven.

To gain conclusion in group work on:

1. Future perspectives for battery electric buses,
2. Future perspectives for charging technologies and concepts, and
3. Identification of key aspects for battery electric bus systems in an urban environment.

The key aspects summarizing the workshop, which are described in detail in the following chapters, are:

- Key drivers for battery electric buses,
- Clean Vehicles Directive,
- Charging systems,
- Fleet management,
- Performance indicators,
- Other low- or zero-emission bus systems,
- Environmental aspects,
- Current trends, and
- R&D issues.

The documentation of the workshop is in Annex 4.2.

2.2.3 Key drivers for battery electric buses

The system of battery electric buses in combination with adequate charging infrastructure has been demonstrated globally in various European, Asian and American countries. Within the workshops, the different main drivers for the now starting broad market introduction of battery electric buses were identified. These key drivers are:

- Climate protection and decarbonisation of the transportation sector,
- Diminishing local air pollution in cities and densely populated areas,
- Expanding the supply of more public transport services for climate friendly mobility, to motivate more people to use public transport especially also in the countryside,
- Establishing new bus lines are the most rapid short-term option to increase public transport services compared to installing new tram and metro lines,
- From supply to demand orientation in public transport, new public mobility services are necessary,
- Initiate first systems for a so called "hybrid public transport" in future, which is the integration of autonomous vehicles in public transport,
- The European Green Vehicle Directive – further details see chapter 1.1.2,
- "Green deal" in Europe: significant GHG reduction until 2030 and climate neutrality in 2050,
- Innovation of new vehicle and propulsion systems,
- Development of new value chains and business models,
- Technology and industry development for global market,

- Digitalization and mobility as a service (MaaS),
- Increasing renewable electricity generation,
- Sector coupling: efficient use of excess renewable power,
- Circular economy, and
- The expectation is *"that 2020 – 2030 will be the "century of battery electric buses in urban environment"*.

2.3 Technological aspects

The technology aspects cover the battery bus technologies, the charging systems and the e-bus systems.

2.3.1 Battery bus technologies

In the last decades, numerous types of electric buses have been developed, which differ mainly in terms of propulsion technology and energy storage system. Figure 5 gives an overview of different types (propulsion systems) of electric buses.

Electric buses are divided into four main categories:

- Hybrid electric buses (HEB),
- Fuel-cell electric buses (FCEB),
- Battery electric buses (BEB), and
- Trolley electric buses (TEB).

Hybrid electric buses (HEB) combine either a conventional internal combustion engine (ICE) drive system or a hydrogen fuel cell drive system (FCHB) with an electric propulsion system in combination with rechargeable batteries.

If the batteries are charged through an external electric power source, it refers to a plug-in hybrid electric bus (PHEB). In contrast, an ordinary fuel cell electric bus (FCEB) does not have extra batteries that are able to power the electric motor directly.

Battery electric buses (BEB) neither have a continuous power supply nor generate electricity on board. Such buses obtain their driving energy exclusively from an on board traction battery, which is mainly charged from external electric power sources (recuperative braking excluded).

Conventional trolley buses are continuously connected to an overhead wire grid, which provides the power supply the entire time. Trolley hybrid electric buses (THEB) are equipped with an auxiliary drive, either an internal combustion engine or a battery/capacitor, which even allows the bus to operate outside the overhead wires for a certain distance/time.

The focus here is on battery electric buses but also taking buses with capacitors and plug-in hybrid buses into consideration.

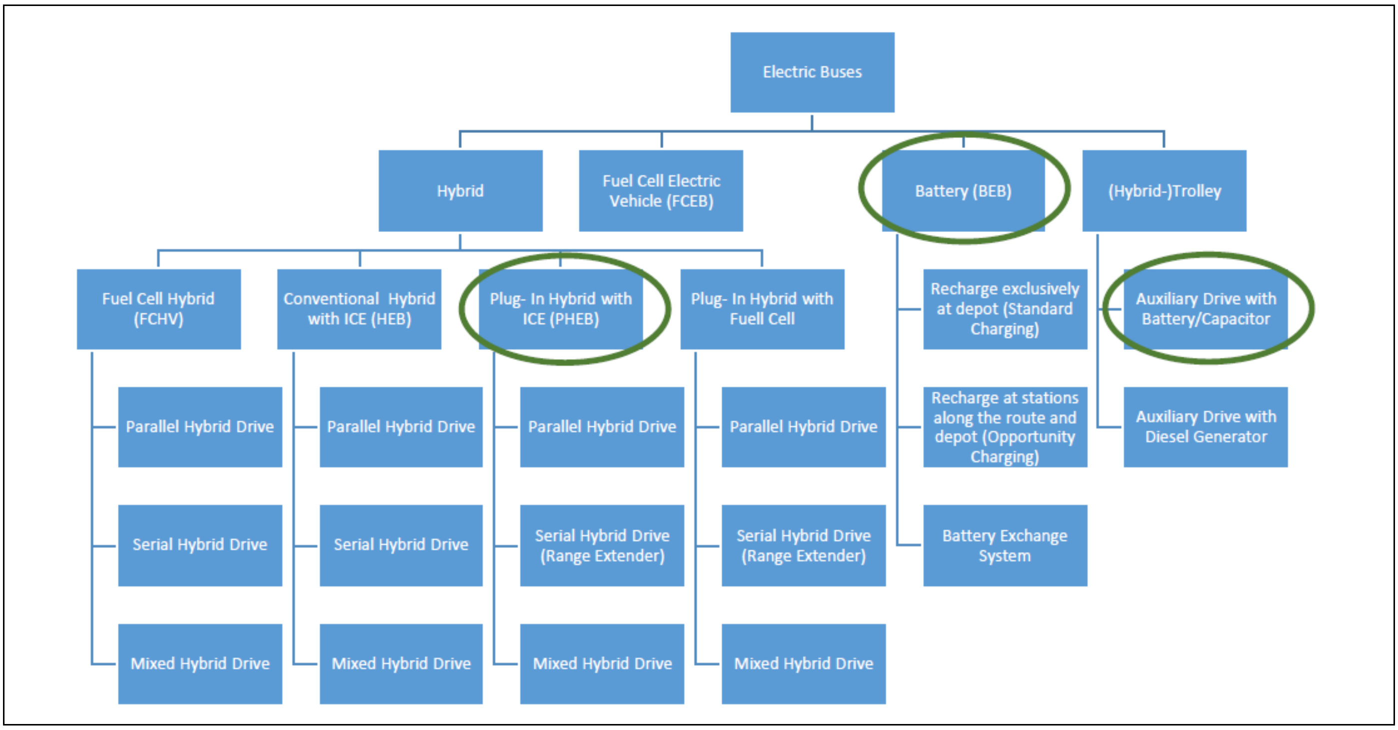


Figure 5: Overview of types of electric buses (Landerl 2016)

There are two main different types of chargers for battery electric buses (Figure 6) the

- Combo-2/CCS plug for depot charging (left), and
- Pantograph upward from schunk (right).

The interoperability of future battery electric buses (of different brands) and charging infrastructure (of different suppliers) is essential for the future success and for taking the right investment decision. In late 2020 an ISO Standard is expected which will guarantee the interoperability. The standard for inductive and wireless charging of battery electric buses should be agreed upon late 2020.

Using the energy of the battery for heating and cooling might reduce the driving range significantly, therefore also diesel heaters are used as an interim solution for the transition period when electrifying bus fleets stepwise. New technologies are under development and tested, e.g. heat pumps.

Figure 6: Combo-2/CCS plug for depot charging (left), pantogragh upward from schunk (right)

Today there are many bus manufacturers offering battery electric buses. More and more bus manufacturers come on the market with e-buses, they are:

- Volvo,
- MAN,
- VDL,
- Hess,
- Daimler,
- Linkker,
- BYD,
- Solaris,
- Van Hool,
- Irizar,
- Proterra,
- Ebusco,
- Ursus,
- Sileo: double articulated e-buses, new generation, Ankara 2nd generation e-buses,
- Deltabus (AT Ternitz): newcomer,
- Scania: new low floor generation,
- Yutong: U12 for Europe,
- EBE Europe:, and
- Midibus: Heuliez, Tribus Movitas.

2.3.2 Charging systems

The charging of battery electric buses can generally be done by using four different methods:

- Conductive, by temporary connection to the electricity grid,
- Inductive, by contactless energy transmission,
- Regenerative breaking, and
- Parallel or serially connected auxiliary drives like ICEs or Fuel Cells.

The main focus of the work in Task 33 was on the two main charging strategies:

- Depot charging (DC) with low power overnight or during the day in the bus depot, and
- Opportunity charging (OC) with high power on the road or end stations of a bus line.

In Figure 7 an overview of the different charging strategies is shown. The charging strategy DC or OC has an influence on the size of the battery and the driving range.

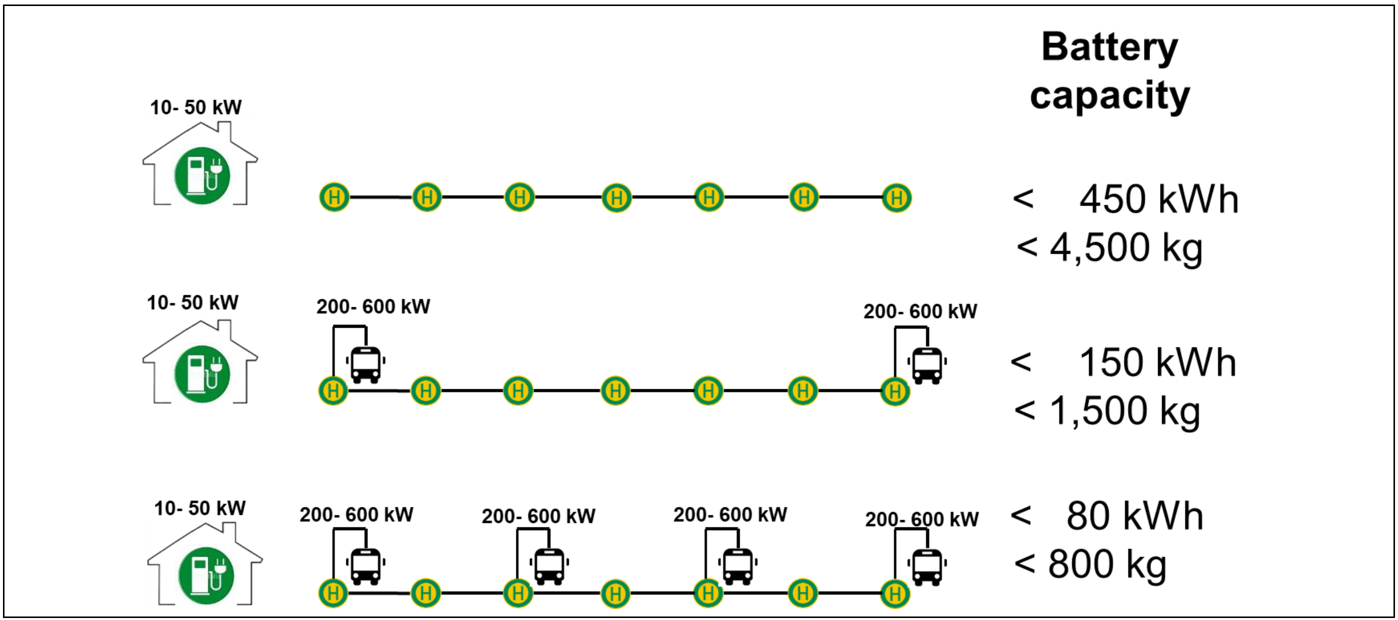


Figure 7: Overview charging strategies

2.3.3 E-bus systems

An e-bus system now combines the charging infrastructure and the battery electric buses to a system to supply transportation services. In Figure 8 examples for current charging regime of selected battery electric bus operations worldwide are shown. These examples show that an e-bus system for daily operations with a high availability can be realised by different charging strategies.

City	Number of vehicles	OEM	Charging regime
Santiago de Chile, Chile	100	BYD	Overnight depot charging with 100 chargers.
Santiago de Chile, Chile	100	Yutong	Charging at terminal.
Indore, India	40	Tata Motor Limited	2 chargers along route.
Kolkata, India	40	Tata Motor Limited	40 chargers.
Leiden, Netherlands	23	Volvo	Charging at terminal.
Nottingham	45	Optare	Charging at terminal and depot.
Paris	23	Bluebus	Overnight depot charging.
Schiphol Airport, Netherlands	100	VDL	Charging at terminal (450 kW) and overnight depot charging (30 kW).
Shenzhen, China	>16 000	BYD, Nanjing Golden Dragon	Mostly overnight depot charging.

Notes: This table includes a selection of recent electric bus projects with at least 20 vehicles. Depots provide parking during non-operating hours while terminals are larger bus stations (e.g. end-of-line station).

Sources: Shenzhen Bus Group (2019); Royal Schipol Group (2019); UITP (2018) and Singh (2019) for Kolkata and Indore, Morris (2018) for Leiden, ZeEUS (2017) for Nottingham and Paris.

Figure 8: Charging regime of selected battery electric bus operations (IEA, Global EV Outlook 2019)

The charging systems in an e-bus system are a very essential part, while talking about battery electric buses. Harmonized charging systems are necessary for fast and/or opportunity charging on the route or in the depot.

Figure 9 shows a qualitative assessment based on experts in Task 33 on the two different charging systems – opportunity charging (OC) and depot charging (DC) assessing:

- Charging technology,
- Operation, and
- Vehicles.

The qualitative assessment of the different aspects of the two different charging systems is done on three levels:

- Solved "+",
- Challenging "-", and
- Neutral "o".

Currently there is no "one fits all charging solution" as the side specific framework conditions have to be considered. For depot charging (110 kV with 25 MVA operation) of a big fleet of battery electric buses the grid connection is a challenge; grid availability is quite high in European cities/countries. For an effective grid load management a charging management of the bus fleet is essential; furthermore a system approach combining bus operation and charging strategies is necessary – bus and charging infrastructure has to be optimally linked.

Aspect	Opportunity charging (OC)	Depot charging (DC)	Remarks
Charging technology			
In depot	o	o	Both system topologies can utilize same depot charging solutions
On route	+	-	OC systems utilize automated connection devices, while DC systems typically have manual connection interface
Power grid connection	o	-	OC: 350 – 500 kW each charger; DC: 10 – 15 MW (100 – 200 buses) each charger 30 – 50 kW
Personnel demand	o	o	-
Investment cost Small fleet Big fleet	 - +	 + -	Low TCO is possible (scalability) - DC with low/mid utilization - OC with high utilization
Operation			
Line management	o	+	OC more sensitive to charging system disruptions but higher battery capacity solves that DC has smaller but more reliable operational range requiring adaptation in operation schedule.
Turn times	o	+	OC charging time at turn
Circulation	+	-	-
Personnel demand	o	-	More drivers for more buses of DC
Rail replacement traffic	+	-	-
Vehicle			
Number of buses	+	-	More buses needed for DC
Zero emissions	+	o	Often fuel heating for DC and OC in some Northern countries
Technology	o	o	-
Personnel qualification	o	o	-

„+“ **solved**
„-“ **challenging**
„o“ **neutral**

Figure 9: Assessment of charging technologies

2.4 Experiences from demonstration projects

In Europe, the following European projects are most relevant in demonstrating and preparing the broad market rollout for battery electric buses in cities:

- ZeEUS – Zero Emission Urban Bus Systems (finished: http://zeeus.eu/),
- ELIPTIC – Electrification of Public Transport in Cities (finished: http://www.eliptic-project.eu/), and
- ASSURED - boosting the electrification of urban commercial vehicles and their integration with high power fast charging infrastructure, evaluating several infrastructures in different cities across Europe (ongoing: https://assured-project.eu).

Currently there are three main charging strategies under demonstration and testing, whereas combinations are realised:

- Overnight (slow) charging in the depot, which requires buses with a high battery capacity (> 300 kWh),
- Opportunity fast charging at final stops, and
- Opportunity fast charging at intermediate stops, which needs the lowest battery capacity (< 100 kWh) but a highly developed charging infrastructure with adequate grid connection.

The current experiences and assessment show no clear advantages or favour for one of these three charging strategies, as it totally depends on the local conditions of the line served and available infrastructure (e.g. bus depot, public space available for charging, battery costs and their future development, grid connection). In general, it can be observed that there are more demonstration projects with opportunity charging at final or intermediate stops. In some cities, also battery electric buses using a range extender with hydrogen and fuel cells are under consideration and tested to enlarge the driving range and limit the battery capacity.

In Figure 10 the Geneva's high capacity e-bus L23 is shown. This was one of the most innovative early European projects combining a small battery capacity in an 18 m bus (about 80 kWh) with a high power opportunity charging infrastructure at the bus stations with many but very short charging times.

Figure 10: Geneva's high capacity e-bus L23 (tpg 2018)

The main lessons learnt from demonstration projects are:

- Gradual vehicle introduction depending on knowledge of public transport operator (PTO) and technology chosen to ensure service operation,
- Paradigm shift from vehicle procurement to system procurement,
- Early stakeholder involvement in the planning, joint feasibility study,
- IT supporting fleet monitoring to optimise operation,
- Identification of main elements needed for "local" LCC (Life Cycle Cost) model, and
- Integrating e-bus services into the overall city transport decarbonisation/defossilisation strategy.

2.5 Rolling out of battery electric bus fleets in the Netherlands

Based on these experiences described in chapter 2.4 it was Eindhoven in 2016 and Amsterdam in 2018 that started the "big roll out" of e-bus fleets as an European frontrunner in the Netherlands. Some of these experiences in the Netherlands are described in the following chapter (based on Kraaijvanger 2019).

2.5.1 Ambition and overall context in the Netherlands

The "Zero-Emission Policy" in the Netherlands requires that:

- From 2030 (or earlier if possible), bus transport services must operate with 100% zero-emissions,
- From 2025, every new bus has to be zero-emission and must use 100% renewable energy or fuel.

To achieve this goal, the Netherlands has:

- Developed a long-term vision based on an integrated approach with political and private partners ('co- creation'),
- Established a commitment to no sustainable transport without sustainable energy ('well to wheel'), and
- Created a stable investment climate, which includes government grants.

2.5.2 E-bus fleets in Amstelland-Meerland and Eindhoven

2.5.2.1 E-bus fleet in Amstelland-Meerland (AML)

The key issues in Amstelland-Meerland for an e-bus-fleet are:

- Operations commenced in 2018,
- Implementation of 100 zero-emission buses in a 24/7 operation,
- Large network with high frequency services,
- Airport and city environment,
- Implementation period of just one year,

- Large road infrastructure works ongoing, and
- New metro line introduced during first year of concession.

The networks statistics in Amstelland-Meerland are (see AML services in **Fehler! Verweisquelle konnte nicht gefunden werden.**):

- 24/7 operation,
- 30,000 e-kilometres every day,
- 160,000 fast charging sessions every year,
- Electricity consumption per year is equal to 3,400 families,
- CO_2-reduction of 15,000 tons every year, and
- 100 articulated electric buses at the start of the contract – heading towards around 250 electric high capacity buses in 2020.

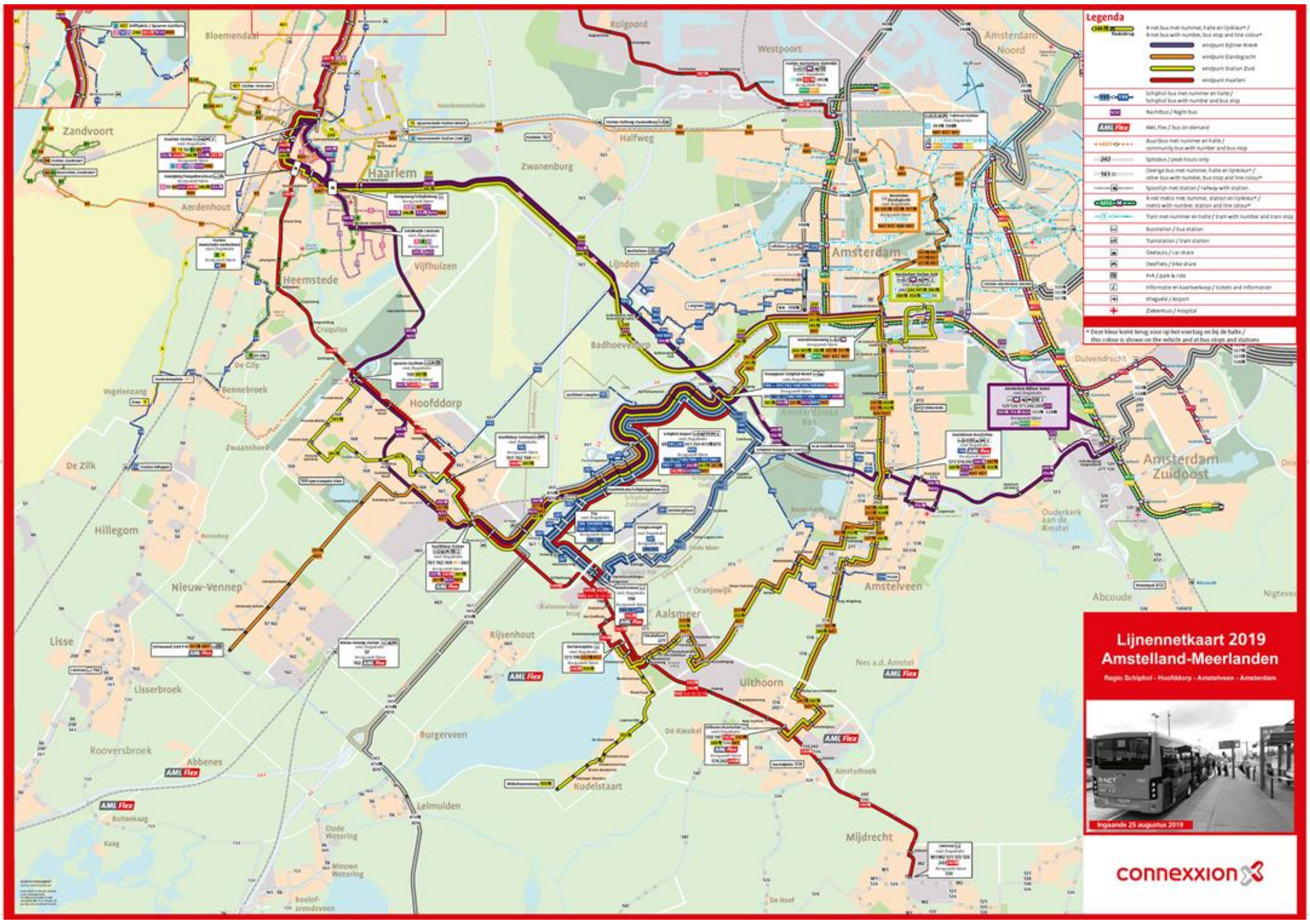


Figure 11: AML services (Kraaijvanger 2019)

2.5.2.2 E-bus fleet in Eindhoven

The key issues in Eindhoven (ZOB) for an e-bus-fleet are:

- Operations commenced in 2016,

- Implementation of 43 18 m buses,
- According to the Green Deal, and
- Lessons learned from ZOB were used when implementing AML.

The networks statistics in Eindhoven are (see ZOB services in Figure 12):

- Reliable e-bus operation,
- Mileage since December 2016: 8.5 million kilometre,
- State of health of battery after 2.5 years: higher than expected,
- This year, diesel buses on Lines 2 and 4 were replaced with e-buses – saving an extra 70,000 litres of diesel each year, and
- 43 articulated electric buses with 18 m length at the start of the contract – heading for a total fleet of around 220 electric buses by the end of 2024.

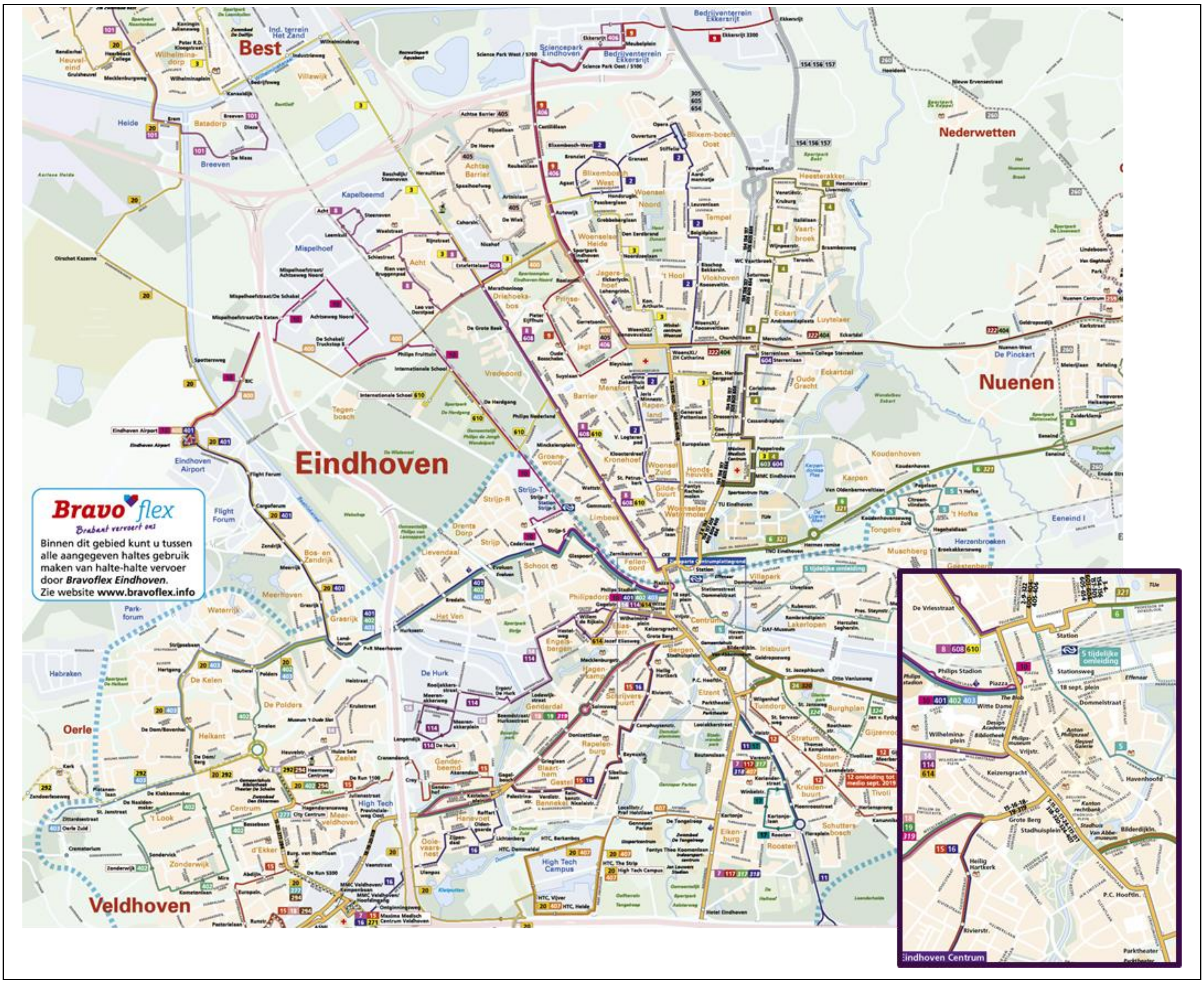


Figure 12: ZOB services (Kraaijvanger 2019)

2.5.3 Challenges for the operator

The main challenges for the operator were:

- A limited number of bus and charging infrastructure suppliers was available with relevant experience,
- The zero-emission fleet has an impact on the required grid capacity and support grid providers, and
- Various new charging infrastructure locations were required in dense/airport environments.

2.5.4 Approach for realisation

The steps towards zero-emission implementation are shown in Figure 13 and cover the following:

- Start with zero-emissions ambition,
- Analyse bus types and features,
- Set up a timetable,
- Analyse environmental factors,
- Analyse necessary infrastructure for charging and grid connection,
- Develop charging strategy,
- Analyse additional needs for bus drivers,
- Set up a financial plan, and
- Finalize zero-emission strategy and transition plan.

In Figure 14 the approach for bus scheduling using a tool box is shown, which was developed in cooperation with academic partners and bus manufacturers.

In Figure 15 the charging strategy of AML is shown consisting of a combination of fast opportunity charging on the route as well as fast and slow charging in the depot. The slow charging is needed to balance the batteries regularly.

In Figure 16 the 4 charging locations of AML with their key data are shown.

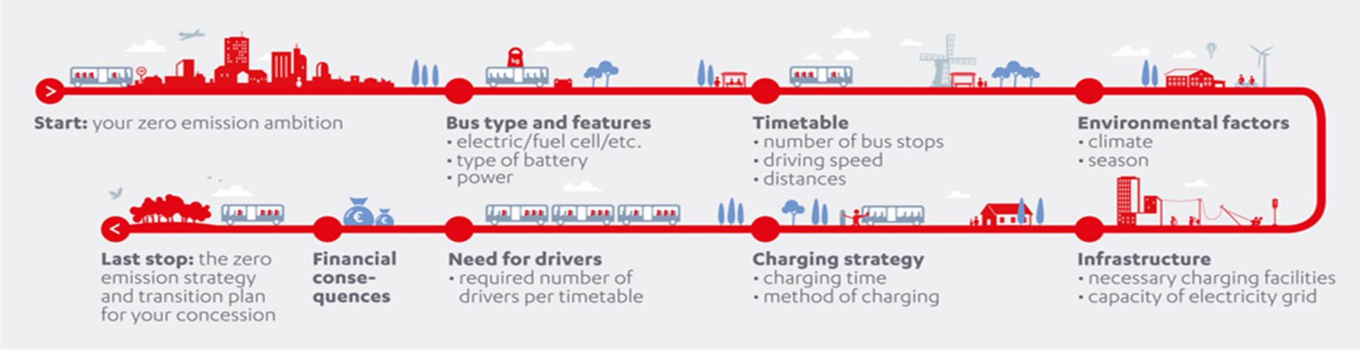


Figure 13: Steps towards zero-emission implementation (Kraaijvanger 2019)

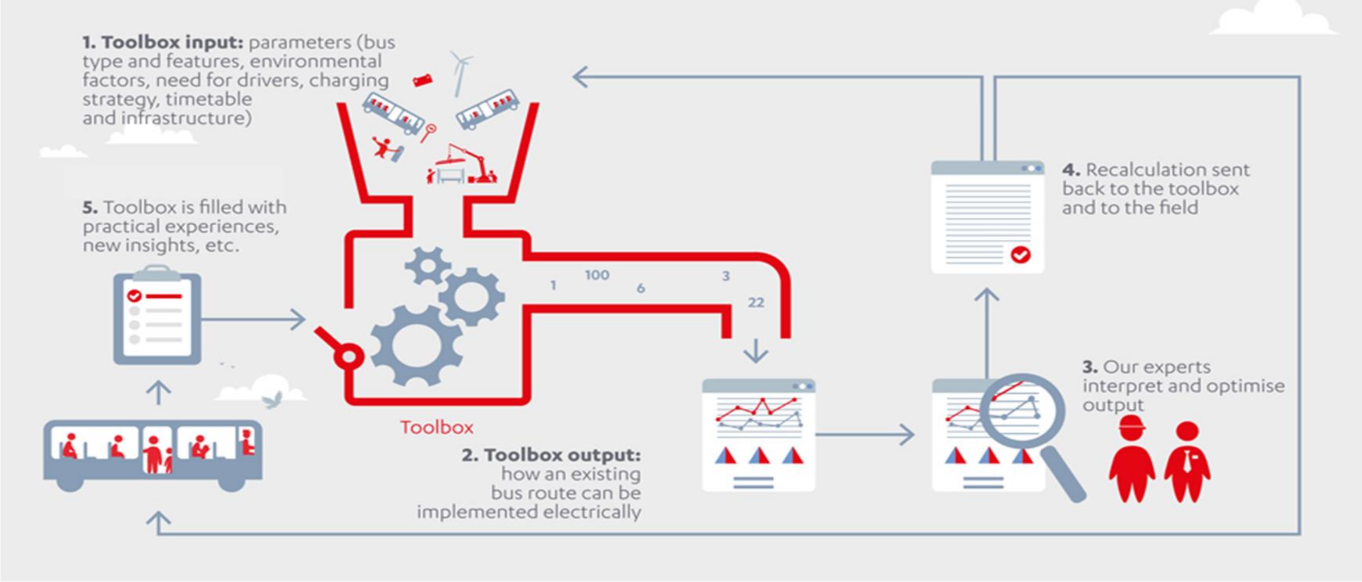


Figure 14: Approach for bus scheduling using a tool box (Kraaijvanger 2019)

Figure 15: Solution AML - Charging strategy (Kraaijvanger 2019)

Figure 16: Solution AML - Charging locations and their key data (Kraaijvanger 2019)

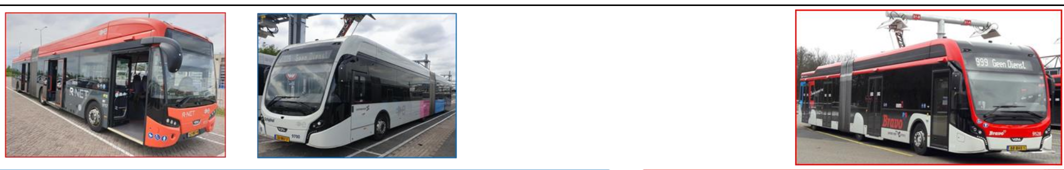
In Figure 17 the e-bus specifications of AML are shown and compared to ZOB in Figure 18. The main difference is that in AML the charging power with 450 kW is higher than in ZOB with 300 kW. The Schunk pantograph of e-buses at AML is above the front axle whereas at ZOB the pantograph is above the middle axle.

- Design : Citea BRT Hello Goodbye design, wheel covers on 2nd and 3rd axle
- Length : 18.1 m
- Capacity : 45 seats / 79 standing (124)
- Doors : 1-2-2-2

- Design : Citea R-Net design
- Length : 18.0 m
- Capacity: 49 seats / 78 standing (127)
- Doors : 2-2-2-0

Technical specs:
- Driveline : Siemens 210 kW central motor
- Battery : Microvast, Highpower, 169 kWh, coolant conditioned, R100.2
- Charging : Slow, Combo 2 plug connector, 60 kW
  Fast, Schunk pantograph above front axle, 450 kW
- Climate System : Thermo King
  Brake Energy Heat Module with auxiliary circulation pump
  Increased efficiency heat pump, floating setpoint for passenger area (climate strategy)
  Additional bio-diesel heater

Figure 17: E-bus specifications AML (Kraaijvanger 2019)



- Design : Citea BRT Hello Goodbye design + R-net
- Length : 18.1 m / 18.0 m
- Capacity : 45 seats / 79 standing (124) + 49 s /78 st (127)
- Doors : 1-2-2-2 + 2-2-2-0

- Design : Citea BRT Bravo design
- Length : 18.1 m
- Capacity: 47 seats / 89 standing (136)
- Doors : 1-2-2-2

Technical specs:
- Driveline : Siemens 210 kW central motor
- Battery : Microvast, Highpower, 169 kWh, coolant conditioned, R100.2
- Charging: Slow, Combo 2 plug connector, 60 kW
  Fast, Schunk pantograph above front axle, 450 kW

Technical specs:
- Driveline : Siemens 210 kW central motor
- Battery : Durapower, NMC, 180 kWh, aircooled
- Charging: Slow, Combo 2 plug connector, 60 kW
  Fast, Schunk pantograph above middle axle, 300 kW

- Climate System: Thermo King
  Brake Energy Heat Module with auxiliary circulation pump
  Increased efficiency heat pump, floating setpoint for passenger area (climate strategy)
  Additional bio-diesel heater

Figure 18: Comparison e-bus specifications of AML (left) and ZOB (right) (Kraaijvanger 2019)

2.5.5 Monitoring of e-bus system

The monitoring and optimization of the e-bus fleet system is essential. As shown in Figure 19 the monitoring and drive-style coaching creates benefits for drivers and business. This system started already in the "diesel era". The monitoring system for e-bus fleets combines the monitoring of the individual e-buses (Figure 20) and the individual charging station/points (Figure 21) to guarantee a mobility service system with a high reliability and to identify further possibilities for improvement.

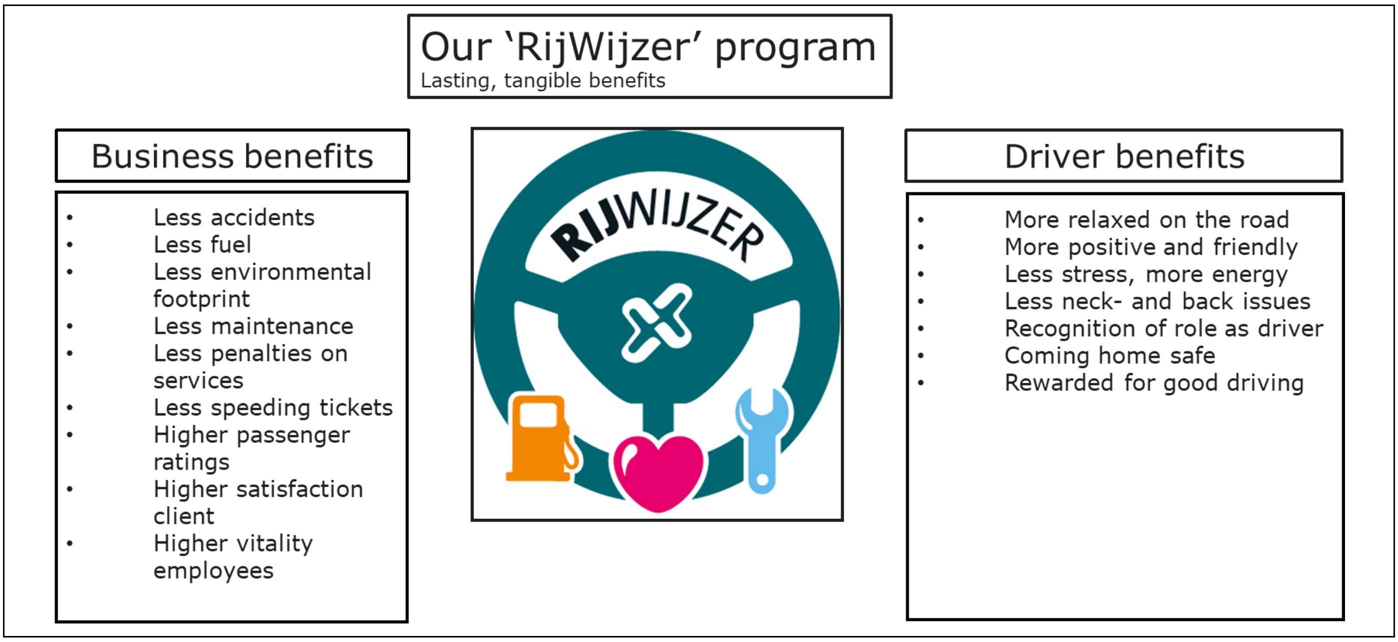


Figure 19: Monitoring and drive-style coaching system (Kraaijvanger 2019)

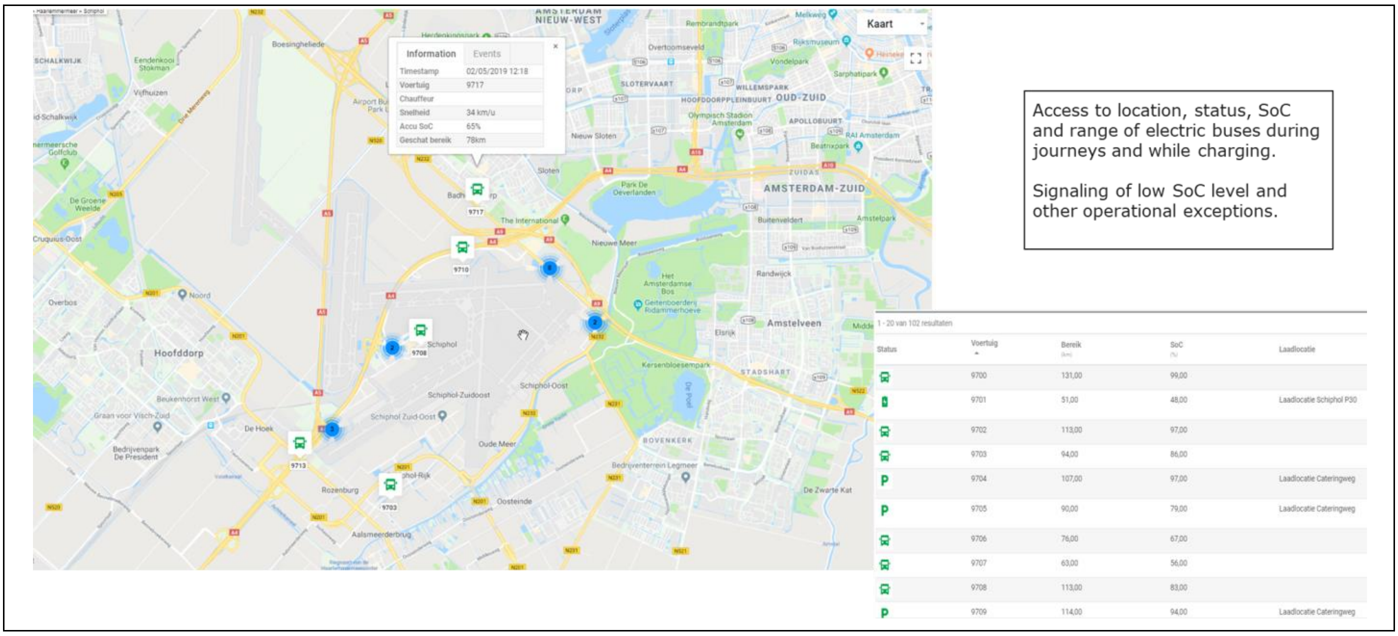


Figure 20: Monitoring of e-buses (Kraaijvanger 2019)

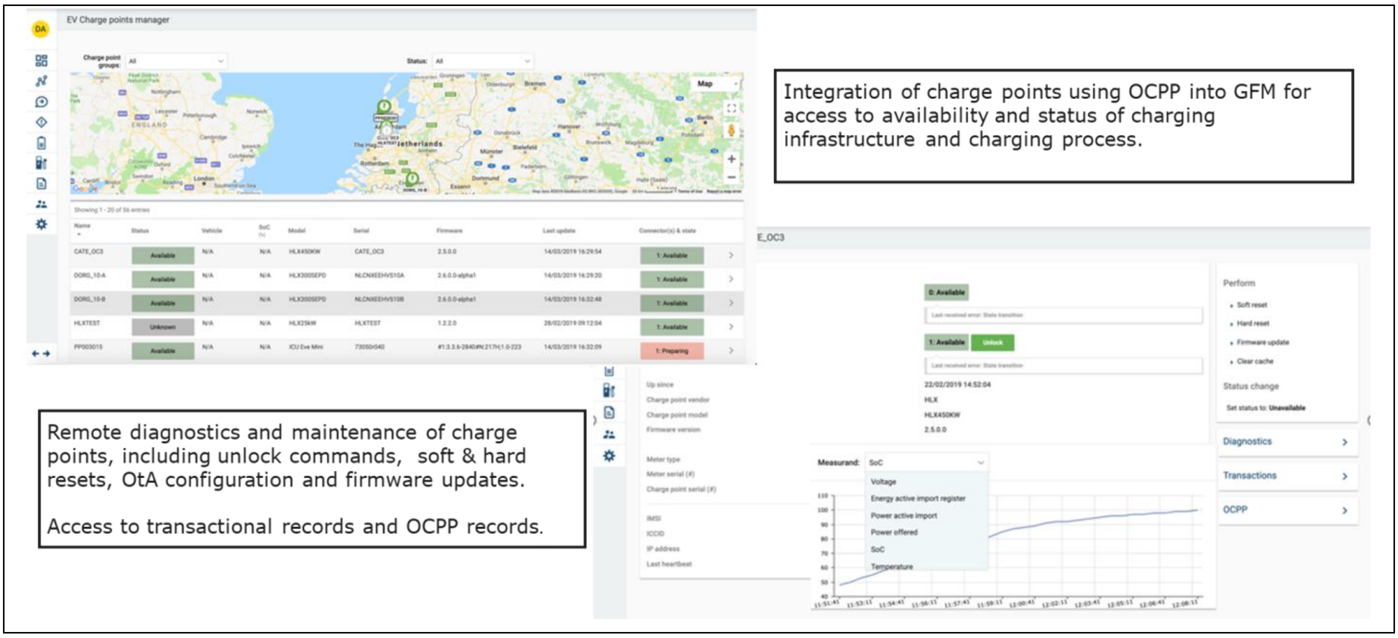


Figure 21: Monitoring of charging stations (Kraaijvanger 2019)

2.5.6 Success factors for e-bus fleet implementation

From the experiences in the Netherlands, it is concluded that the “zero-emission challenge” is changing the game. The benefits of electrification are established in terms of pollution and noise reduction; however, electric fleets bring new challenges for operators.

The main challenges and choices in the transition to an electric operation include:

- Finding the most appropriate technology according to operational needs,
- Involving new stakeholders such as utilities providers and civil works contractors,
- Developing new skills internally, particularly in the areas of planning, driving and maintenance,
- Monitoring system for buses and chargers are very important for a reliable operation, and
- How best to move from a diesel bus to an e-bus system – a phased wise e-bus implementation is advised instead of a big bang.

The “Golden Rule” gained from these experiences in the Netherlands says: *“The realisation of the grid connection in time is crucial”*.

2.6 Fleet Management

One very important aspect for the further future development of battery bus systems is an advanced fleet management. Fleet management can be utilised to optimise the operation of electric bus systems. Especially when high scale OC bus systems are considered, fleet management has functions to ensure optimal charging operations. For example, system reliability can potentially be improved by charging priorisation, which ensures the buses should always have sufficient charge before departure. Moreover, the utilisation of the existing infrastructure and electric bus component (battery) aging can also be improved by smart charging applications that avoid unnecessary high charging powers. For instance, if a bus has relatively high state of charge and long turnaround time, lower charging power may be used to decrease the charging stress on battery and even out power demand from the grid. In addition, fleet management could also perform active monitoring on certain indicators on the fleet. For example, tracking component state of health, suggest more optimal duty cycle circulation to even out the wear of the fleet. Fleet management applications are still mostly in the development phase at this time.

2.7 Performance indicators

The key performance indicators for battery electric bus systems are:

- Operating costs and energy consumption:
  - Energy costs for driving (€/km): including electricity (from grid) and heater fuel,
  - Operational driving distance (%/km): operational (on route) distance driven compared to the planned bus circulation,
  - Total electricity consumption (kWh/km): total charged external energy (from charger) / kilometres driven (both on route and total km's),
- Charging system performance:
  - Time required positioning the bus at the charger (s - seconds): time to manoeuvre the bus to the charger. From arrival at the charger proximity to the point when the driver initiates the charging,
  - Total charging time (s): charging duration per sequence step from the charging start command to bus being ready to leave,
  - Charging node utilization (%): time when the charging position is occupied / time available. Time occupied includes the active and dead times,
- System performance:
  - Depart on schedule (%): percentage of departures left on schedule,
  - Availability of the vehicles (%): percentage of the time that the vehicles have been available for service, and
  - Availability of the infrastructure (%): percentage of time when charging service is available / calendar time.

As additional indicators, the following are relevant:

- Powertrain electricity consumption (kWh/km): inverter consumed electricity/kilometres driven (on route),
- Heating electricity consumption (kWh/km): electricity consumed by the Heating/Ventilation/Air Conditioning (HVAC) system (both on route and total),
- Auxiliaries electricity consumption (kWh/km): electricity consumed by other electric auxiliaries, such as power steering, air compressor and DC/DC (on route),
- Fuel consumption (l/h): fuel heater fuel consumption vs. temperature,

- Charging efficiency (%): electricity from the grid/electricity into the battery,
- Dead time in charging (%): dead time in charging total charging time,
- Battery efficiency (%): electricity out from the battery/electricity into the battery,
- Total system energy efficiency (%): electricity out from the battery/electricity from the grid,
- Minimum “State of Charge – SoC” in operation: lowest battery state of charge in operation,
- Average delta SoC in operation: estimate from operational data, and
- Battery health, (“State of Health – SOH”): percentage of the remaining battery capacity versus battery nominal capacity.

2.8 Environmental aspects

2.8.1 Methodology

The environmental aspects of battery electric buses can only be assessed on the basis of Life Cycle Assessment (LCA) taking the entire life cycle into account – production of the bus (incl. battery) and the infrastructure, operation of the bus including the supply of the electricity and the end of life management of the facilities, e.g. recycling, reuse. The environmental effects deriving from LCA must be compared to a diesel bus (and hydrogen fuel cell bus if of interest).

The LCA can be described the following:

Life cycle assessment is a method to estimate the material and energy flows of a product (e.g. transportation service) to analyse environmental effects over the entire life time of the product „from cradle to grave”.

The environmental effects of the various stages in the life cycle of the transportation systems with passenger vehicles are investigated. The stages include extraction of raw materials, manufacturing, distribution, product use, recycling and final disposal (from cradle to grave) (Figure 22). Life cycle assessment allows the comparison of different systems offering the same transportation service during the same time period and identifies those life cycle phases having the highest environmental effects.

The most important word in the LCA definition is “estimated“. All environmental results based on LCA are an estimation, as it is not possible to identify all environmental contributions in the life cycle of a transportation system totally. But due to the strong development of LCA and its databases in the last 20 years the most relevant influences can be identified and calculated on the GHG emissions and the primary energy consumption of different transportation system.

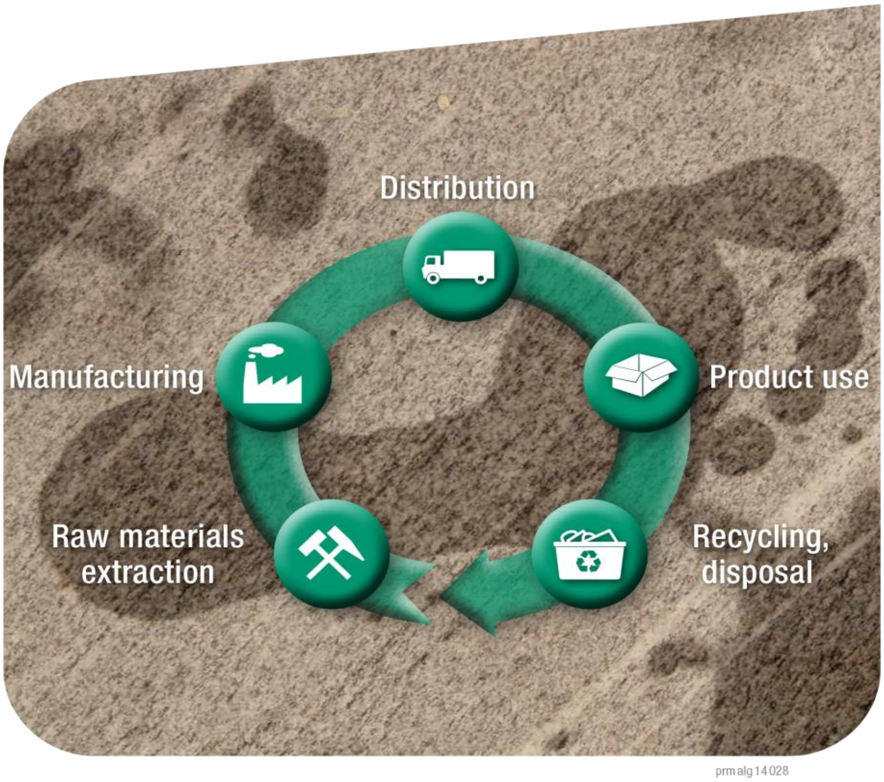


Figure 22: Scheme of life cycle assessment

According to ISO 14,040 a LCA consist of the 4 following phases, which are closely linked during the whole process of applying LCA methodology (Figure 23):

- Goal and scope definition,
- Inventory analyses,
- Impact assessment, and
- Interpretation and documentation.

In the inventory analysis, the mass and energy balance is made along the whole process chain to calculate the physical (primary) energy demand and the physical emission of each single greenhouse gas.

In the impact assessment, the single energy inputs and emissions are aggregated to the cumulated primary energy demand and the global warming effects by applying the global warming potentials to the single GHG emissions.

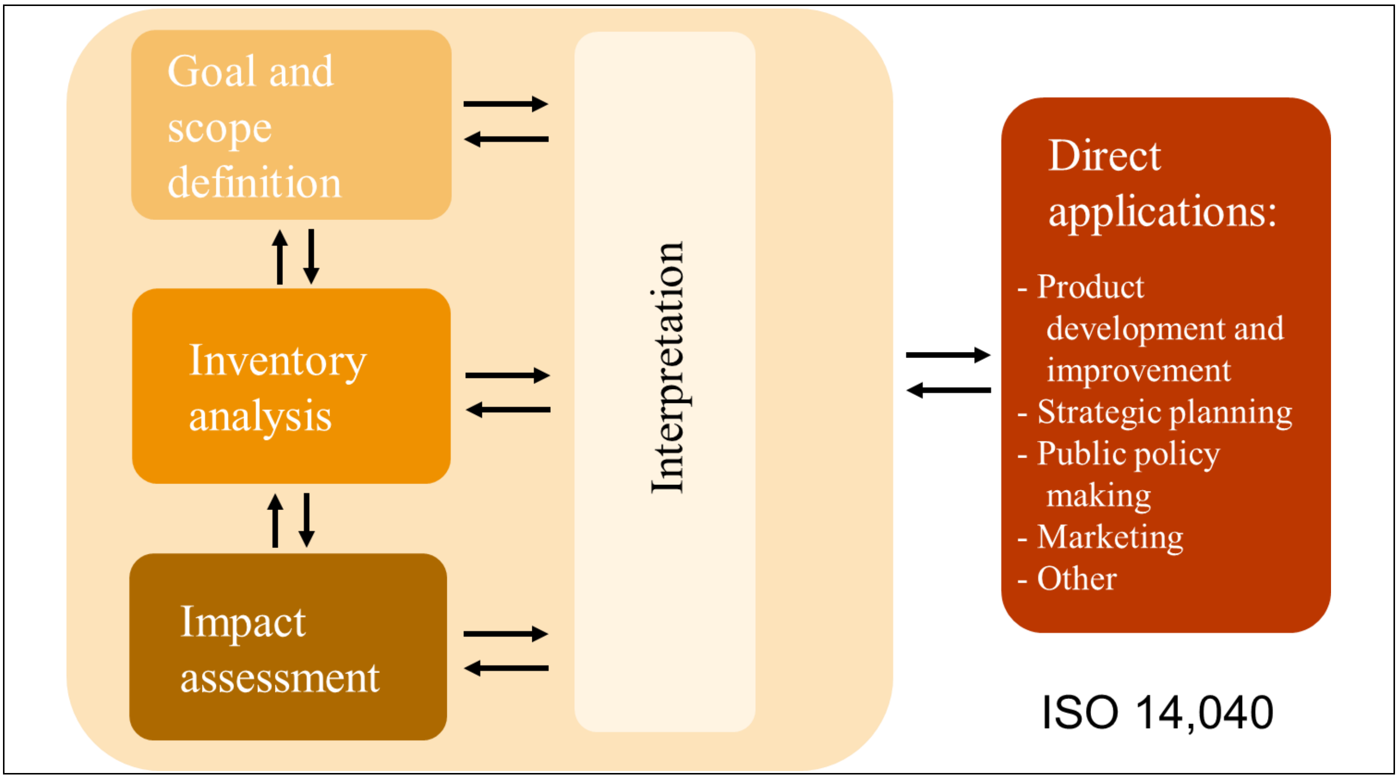


Figure 23: Life Cycle Assessment framework according to ISO 14,040

For providing a transportation service all processes must be analysed from raw material and resource extraction to the vehicle offering the transportation service. The elements and system boundaries of vehicle's LCA include all technical systems using and converting primary energy and material resources to provide the transportation service and contributing to environmental effects.

In Figure 24 the simplified scheme of the process chain for a battery electric vehicle is shown covering the production, the operation and the end of life phase of the system:

- The production phase includes the production of the vehicle and the battery[3],
- The operation phase offers the transportation service by driving the vehicle, charging and fueling infrastructure, electricity grid, electricity production and ends with the extraction of primary energy in nature, and
- The end of life phase includes the dismantling processes of the vehicle and sorting the materials for reuse, recycling and energy generation.

[3] Additionally, also the spare parts are considered in the production phase, which contribute in total very less.

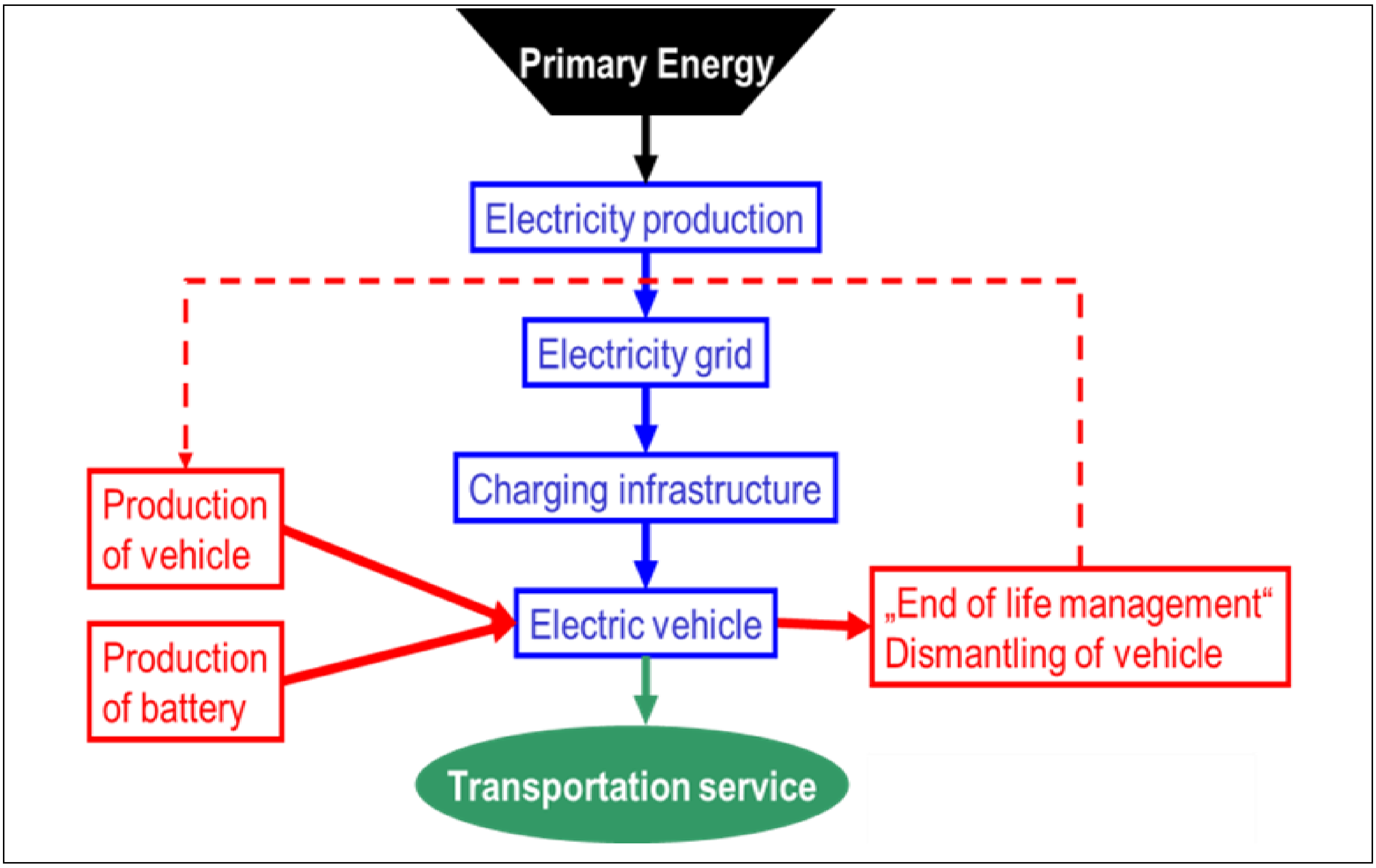


Figure 24: Scope of life cycle assessment - example battery electric vehicle

Life cycle assessment of the three phases in the life cycle of a vehicle – production, operation (including fuel/energy supply) and end of life treatment - cumulates the environmental effects over the whole life time. In Figure 25 this is shown for three hypothetical vehicle types. The cumulated effects over the entire lifetime are then distributed to the transportation service provided in the operation phase (e.g. 150,000 km) to get the specific effects per driven kilometer (e.g. g CO_2-eq/km).

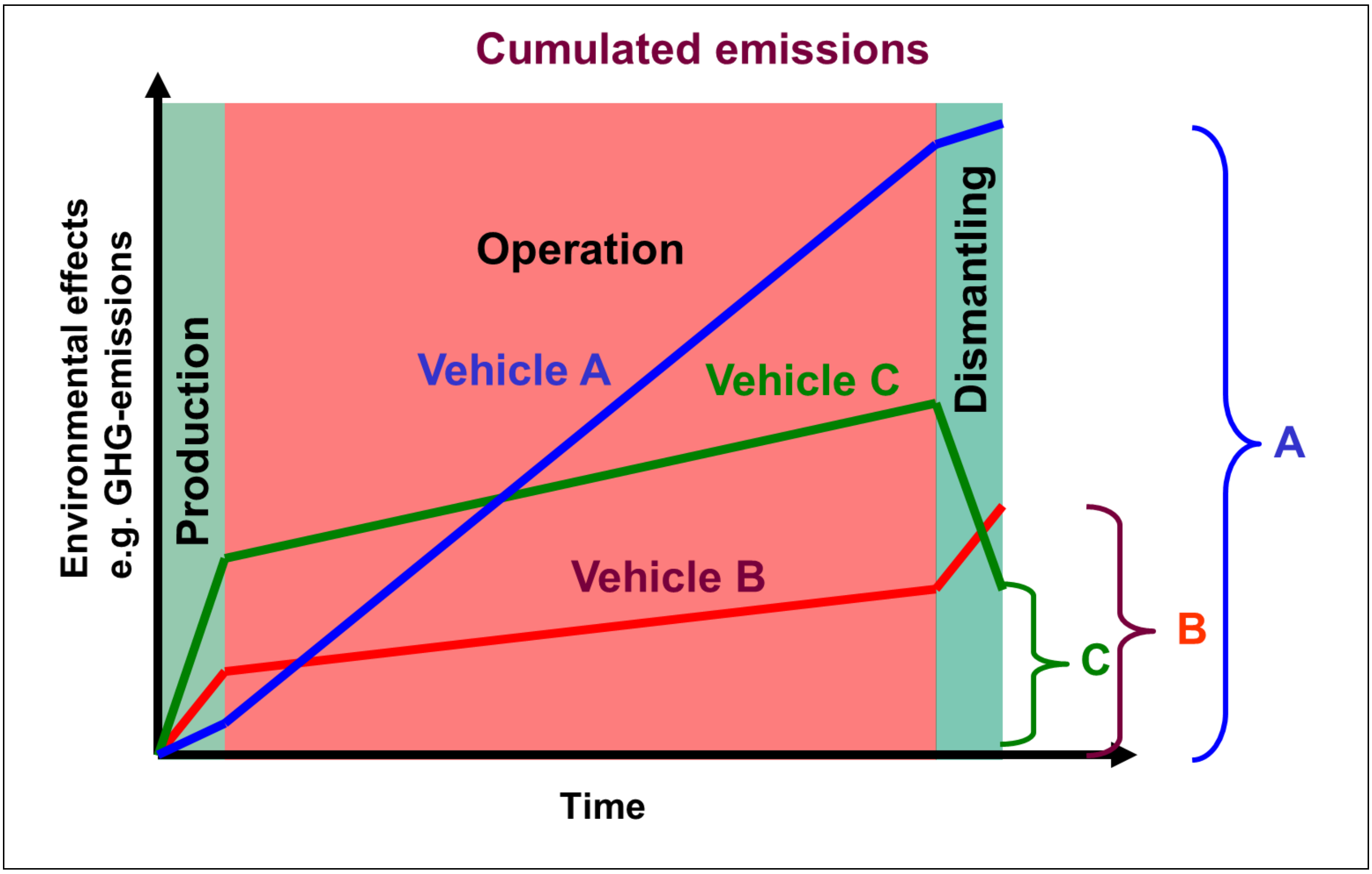


Figure 25: The three phases in the life cycle of a vehicle – production, operation (including fuel/energy supply) and end of life treatment for three hypothetical vehicle types A, B and C

In LCA, the cumulated environmental effects over the lifetime are attributed to the functional unit, which is the service of a system that is provided. In this analysis, the considered transportation systems provide a transportation service with buses. That means that the cumulated environmental effects are attributed to the functional unit of driving 1 kilometer with a bus. As the buses have different capacities of passengers due to weight limitations, the effects are calculated per kilometer and passenger capacity (e.g. g CO_2-eq/(p-km)e. The calculated functional units are:

- GHG emissions in g CO_2-eq/(p-km) covering of CO_2, CH_4 and N_2O, and
- Cumulated primary energy consumption in kWh_{total}/(p-km) giving the share of fossil and renewable energy.

The different possible driving ranges per filling of an internal combustion engine (ICE), battery electric and fuel cell bus are not reflected in this functional unit.

2.8.2 Environmental impacts

Based on the inventory data two impact categories are assessed:

1. Global warming, and
2. Total cumulated primary energy consumption.

Other environmental effects like emissions to air NO_x, SO_2, PM and their consequential impacts like acidification, ozone formation, and human toxicity are not considered.

Global warming

The greenhouse gas emissions – carbon dioxide (CO_2), methane (CH_4) and nitrogen monoxide (N_2O) – are considered.

As measure of the greenhouse effect of these gases the global warming potential (GWP) is used. This gives the contribution of the different gases to the possible global warming and is expressed in form of an equivalent amount of CO_2. The concept of global warming potential was developed to compare the contribution of the different gases to global warming. The global warming effect of a kilogram gas is expressed with a multiple ("equivalent factor") of the effect of one kilogram carbon dioxide. With the equivalent factors the amount of the gases are calculated in amount of CO_2-equivalents (CO_2-eq.):

- 1 kg CO_2 = 1 kg CO_2-eq,
- 1 kg CH_4 = 34 kg CO_2-eq, and
- 1 kg N_2O = 298 kg CO_2-eq.

The biogenic CO_2 emission from the combustion of biofuels is calculated to be zero, as the same amount of CO_2 was up taken during biomass growing via photosynthesis from the atmosphere. This includes the assumption that the biomass is cultivated sustainably.

This accounting system for biogenic CO_2 is used also in the national GHG accounting system following the IPCC guideline for national inventories in the energy sector. Changes and dynamics in the carbon stocks, e.g. the carbon that is stored in plants, litter and soil, in agriculture and forestry are considered in the CO_2 emissions or CO_2 uptake caused by Land Use Changes (LUC) for biomass used for biofuels.

Cumulated Primary Energy Demand

Based on the amount and type of final energy carriers e.g. fuels, electricity, the necessary amount of primary energy is calculated to supply the energy needed for the transportation systems. The following primary energy resources are considered:

- Fossil resources: coal, oil and gas,
- Renewable resources: hydro power, biomass, solar, wind, and
- Other resources: nuclear, waste, residues.

2.8.3 Basic data

In Table 1 the basic data for environmental assessment of the considered bus systems are shown. The following systems are analysed:

- Battery electric bus with opportunity and depot charging,
- Hydrogen fuel cell bus,
- Diesel bus ICE,
- Natural gas bus (CNG – compressed natural gas) with conventional and high pressure direct injects (HPDI) ICE, and
- Renewable gas (CRG – compressed renewable gas made from biomass).

The basic data for these bus systems derive from the cooperation in the Task 33 and LCA data are taken from various data bases e.g. ecoinvent, GEMIS. The data for battery production are taken form the LCA Battery Model of JOANNEUM RESEARCH. The methodology for LCA of electric vehicles (EV) is in line with the results of the cooperation in IEA HEV Task 19 and 30, which is in place since 2012.

The LCA is done with the electricity mix of the following 8 countries, which participate or cooperate in Task 33:

1. Austria (AT),
2. Canada (CA),
3. Finland (FI),
4. Germany (DE),
5. Republic of South Korea (KR),
6. Spain (ES),
7. Chile (Cl), and
8. Renewable Republic (RR) a fictive country with 100% renewable electricity.

The Renewable Republic was defined to show the results, if 100% renewable electricity is used. In Figure 26 the electricity mix in the considered countries is shown. The hydrogen is produced via electrolysis using these electricity mixes.

Table 1: Basic data for environmental assessment of bus systems

	Unit	Battery electric bus		Diesel bus	Hydrogen fuel cell bus	CNG Bus		CRG Bus
		opportunity charging	depot charging	ICE	FC	ICE	HPDI[1)]	HPDI[1)]
Bus length	[m]	12	12	12	12	12	12	12
Capacity	[passengers]	95	84	105	100	105	105	105
Traction energy consumption	[kWh/km]	1.0	1.2	3.5	2.0	4.2	3.5	4.2
Battery nominal capacity	[kWh]	150	355	-	8	-	-	-
Max SoC	[-]	0.8	0.95	-	-	-	-	-
Min SoC	[-]	0.2	0.1	-	-	-	-	-
Reserv SoC	[-]	0.15	0.05	-	-	-	-	-
SoC for auxilliaris	[-]	0.1	0.1	-	-	-	-	-
Usable SoC	[-]	0.35	0.7	-	-	-	-	-
Battery usable capacity	[kWh]	53	248.5	-	-	-	-	-
Driving range/Charge	[km]	53	207	-	-	-	-	-
Charging efficiency	[%]	90%	95%	-	-	-	-	-
Weight (without battery; fuel cell and tank)	[t]	12	12	12	12	12	12	12
Lifetime bus	[a]	12	12	12	12	12	12	12
Lifetime battery	[a]	6	6	6	6	-	-	-
1) High pressure direct injection ICE								

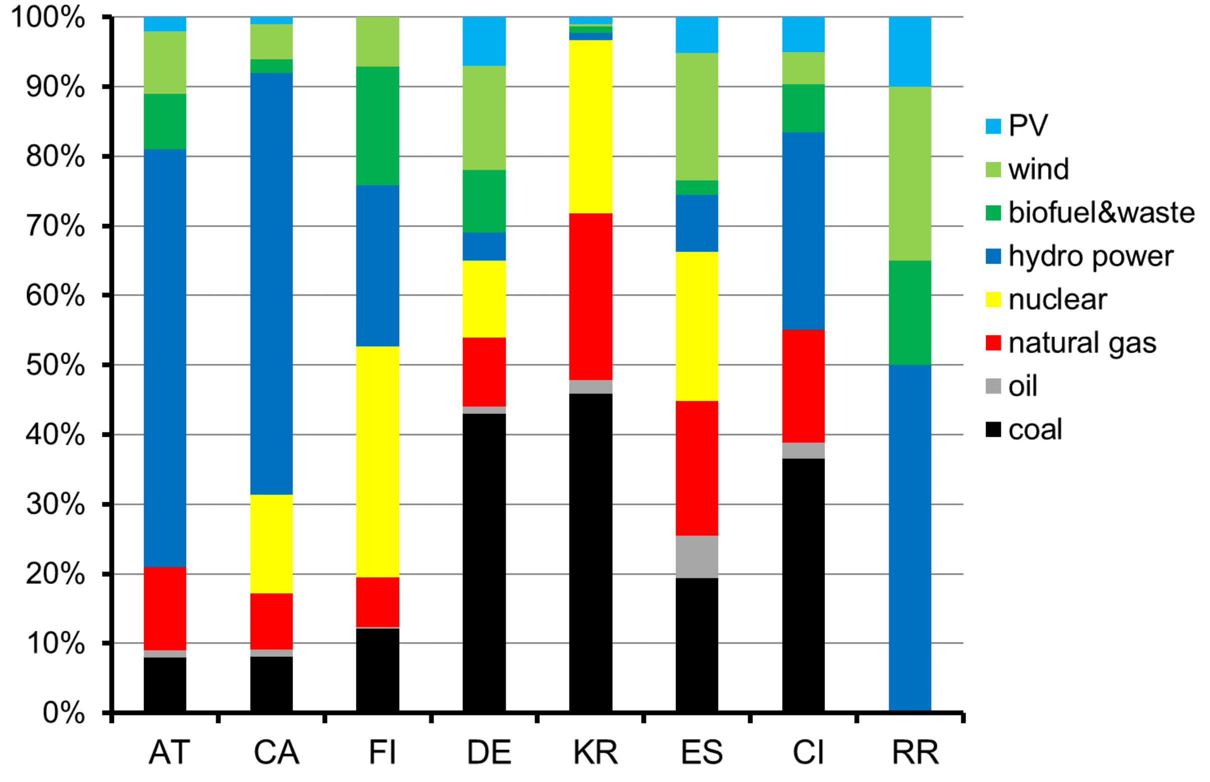


Figure 26: Electricity mix in the considered countries

2.8.4 Charging infrastructure

The LCA results for the charging infrastructure are shown for the GHG emissions in Figure 27 and for the cumulated primary energy demand in Figure 28 for electricity and hydrogen at the charging and filling station. The difference between opportunity and depot charging is very small therefore, it is not shown here.

It can be seen that due to the energy efficiency of producing hydrogen via electrolysis the GHG emissions and the primary energy demand for 1 kWh of hydrogen is higher than for electricity, e.g. using renewable electricity in RR electricity has about 20 g CO_2-eq/kWh and hydrogen about 36 g CO_2-eq/kWh.

The electricity mix has a strong influence on the GHG emissions and the cumulated primary energy demand, e.g. using renewable electricity in RR is 1.1 kWh/kWh and with a high share of coal in KR it is about 2.7 kWh/kWh mainly due to the efficiency of the different power plants.

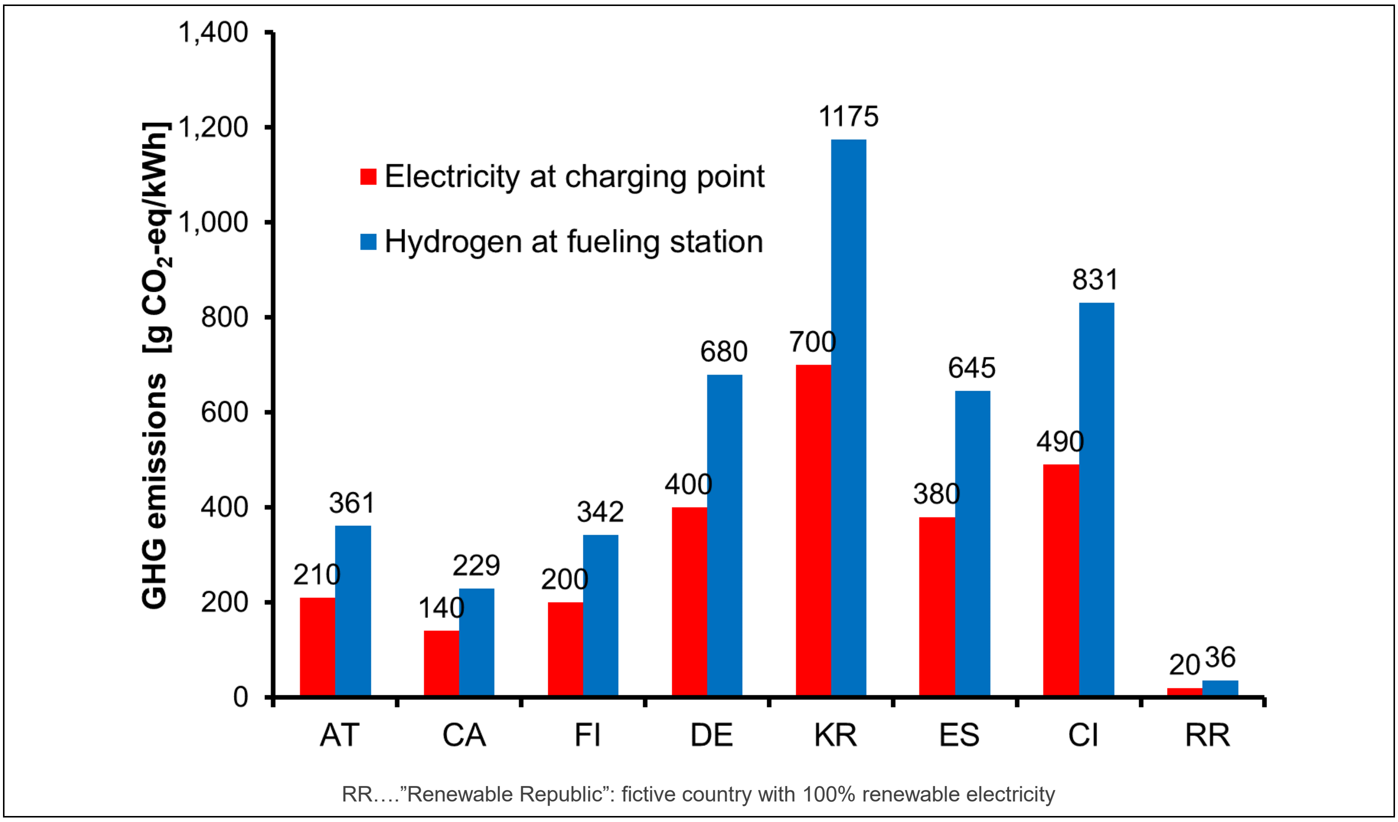


Figure 27: GHG emissions of electricity and hydrogen at the charging and filling station

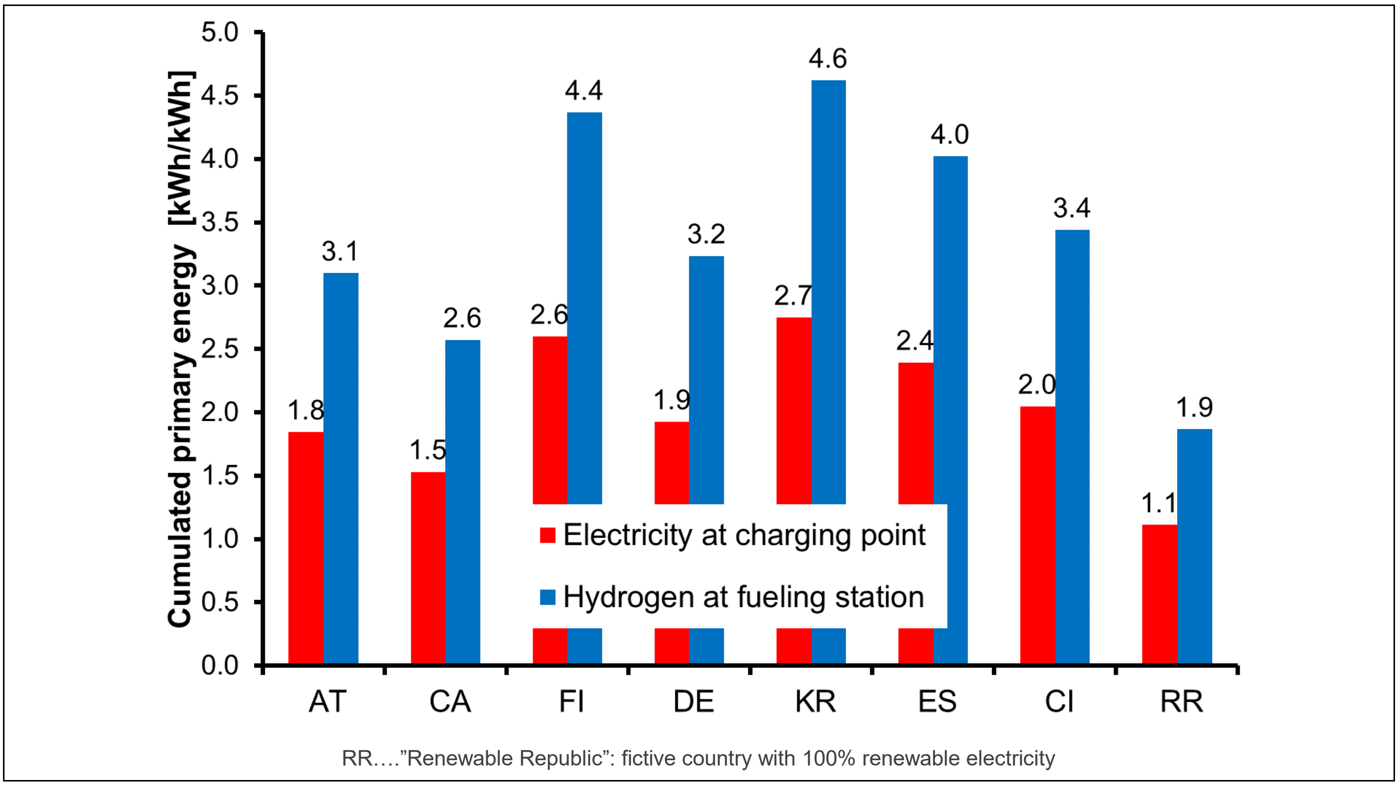


Figure 28: Cumulated primary energy demand of electricity and hydrogen at the charging and filling station

2.8.5 Bus system

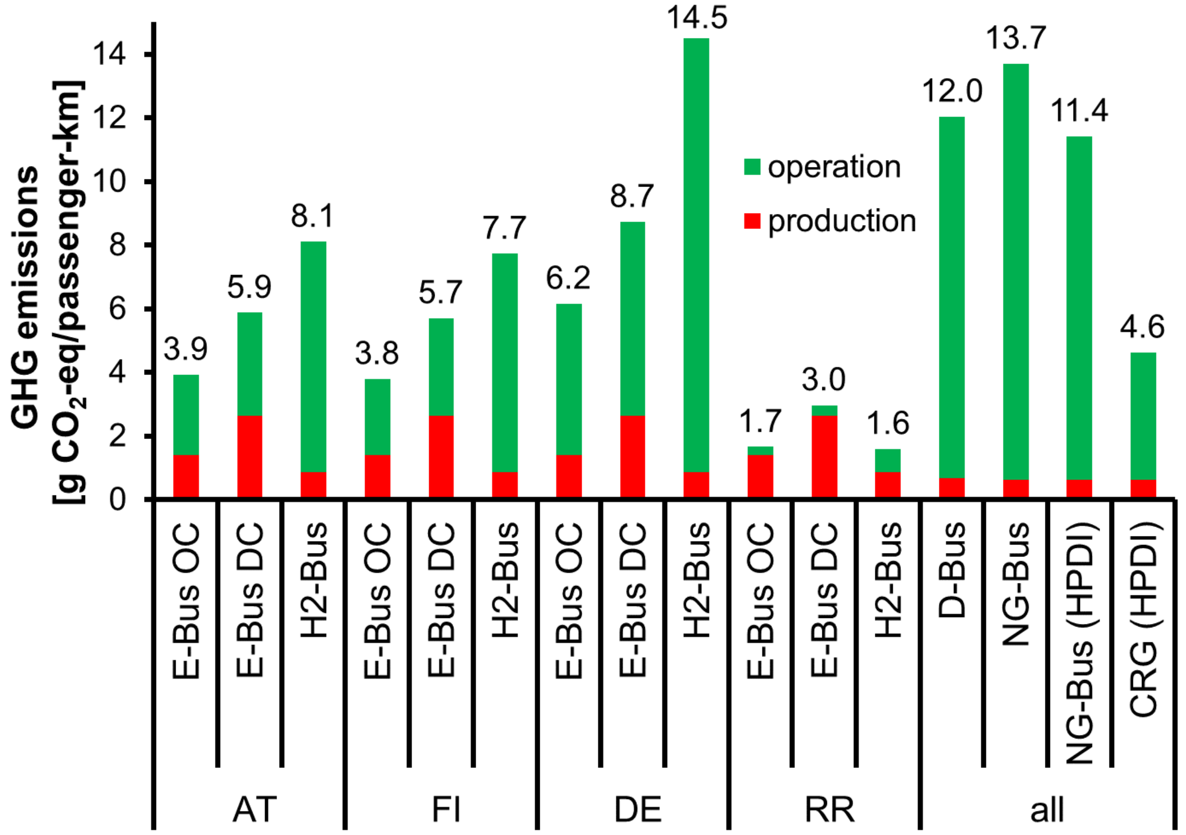
The LCA results for the different bus systems for the GHG emissions are shown in Figure 29. Some countries were selected here for the report, the others were presented in the workshops only.

It can be seen that the buses using renewable electricity have the lowest GHG emissions. The e-bus system using opportunity charging and the hydrogen bus have about 1.6 – 1.7 g CO_2-eq/(p-km). It is interesting to see that the GHG emissions of battery production are significant and using renewable electricity in RR the battery production dominates the results.

In all selected countries, the e-buses have lower GHG emissions than the diesel bus. The natural gas buses have similar GHG emissions than the diesel bus; only CRG has GHG emissions comparable to e-bus systems.

Due to the higher battery capacity and the higher energy consumption per kilometre as well as the lower passenger capacity the e-bus system using depot charging has higher GHG emissions than the e-bus system using opportunity charging.

In all countries, the hydrogen bus system has higher GHG emissions than the e-bus system except in RR, where the production of the battery for the e-bus dominates the GHG emissions even when the hydrogen bus is having higher emissions from its operation. In Germany, the diesel bus system (12 g CO_2-eq/p-km) is having lower GHG emissions compared to a hydrogen bus system using the current electricity mix for hydrogen production (14.5 g CO_2-eq/p-km).



OC….opportunity charging; DC….depot charging overnight;

RR….”Renewable Republic”: fictive country with 100% renewable electricity; D…Diesel; NG….Natural Gas;

HPDI….high pressure direct injection; CRG….Compressed renewable gas (biomethane 40% residues and 60% maize)

Figure 29: GHG emissions: LCA based comparison per passenger capacity kilometre

The LCA results for the different bus systems for the cumulated primary energy demand are shown in Figure 30. Some countries were selected here.

It can be seen that the e-bus systems using renewable electricity have the lowest primary energy demand. The e-bus system with renewable electricity using opportunity charging has a primary energy demand of about 17 kWh/1,000 p-km and with depot charging of about 23 kWh/1,000 p-km.

Due to the higher battery capacity and the higher energy consumption per kilometre as well as the lower passenger capacity the e-bus system using depot charging has a higher cumulated primary energy demand than the e-bus system using opportunity charging.

Due to lower energy efficiency, the hydrogen bus system has a higher cumulated primary energy demand in all countries compared to the e-bus systems.

The cumulated primary energy demand of diesel bus systems with about 45 kWh/1,000 p-km is higher than for the e-buses with about 17 – 45 kWh/1,000 p-km, even in the case that the e-bus systems use a significant share of non-renewable electricity. However, of course the fossil primary energy demand is the highest for diesel and natural gas bus systems.

The bus system using renewable compressed gas has a high cumulated primary energy demand of about 83 kWh/1,000 p-km due to the low conversion efficiency from biomass to biomethane.

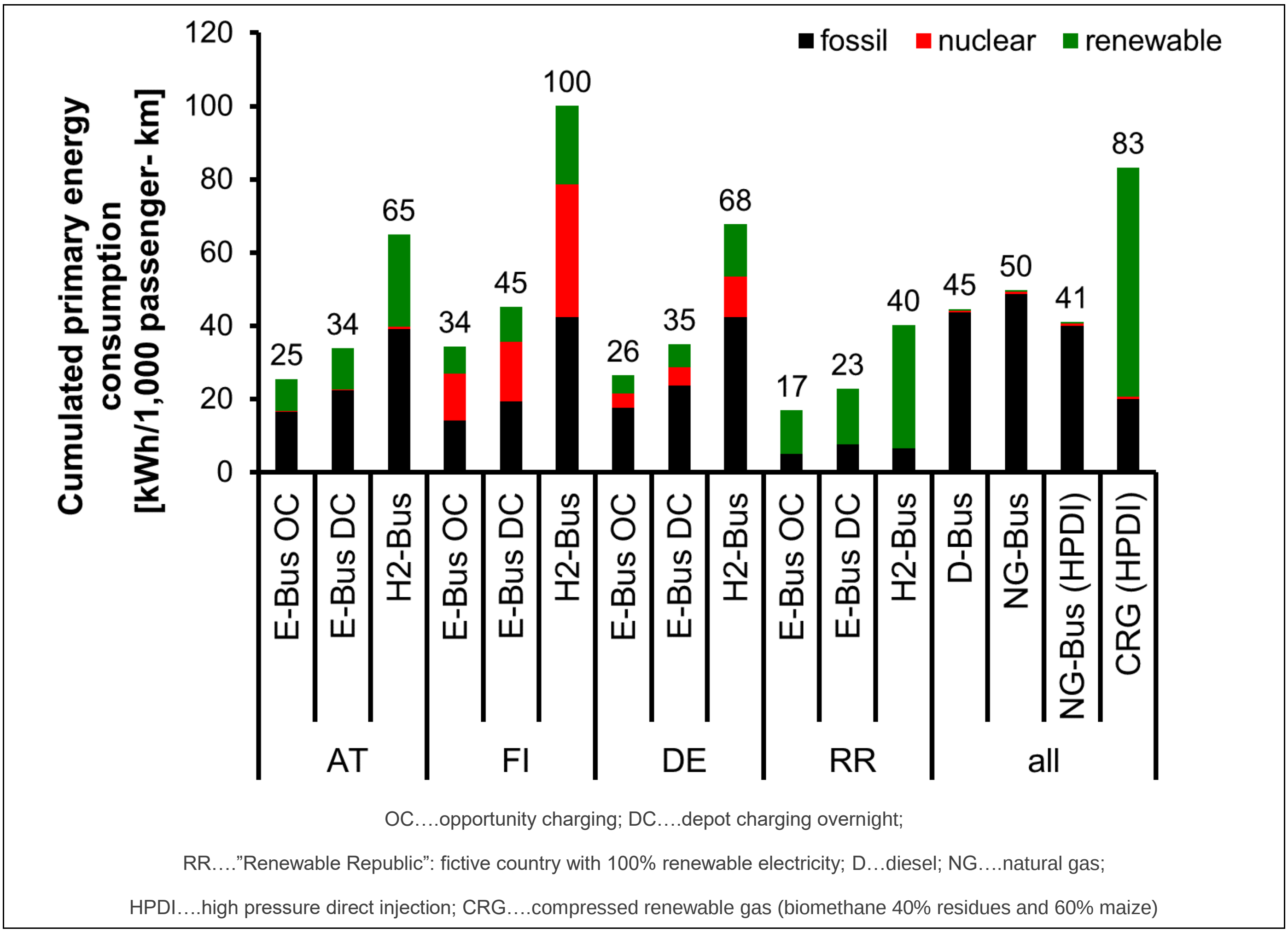


Figure 30: Cumulated primary energy demand: LCA based comparison per passenger capacity kilometre

2.8.6 Main influences

The main influences on the environmental impacts of e-bus systems are identified. The two main influences are the lifetime kilometres - mean all kilometre driven during the lifetime - and the energy consumption of the bus.

In Figure 31 the influence of lifetime kilometres on GHG emissions from bus production for bus systems with 12 m and 18 m buses is shown. It is shown that the longer lifetime kilometre for e-bus systems have a stronger influence than for diesel buses due to the relative high GHG emissions form battery production. As the e-bus systems using depot charging have a higher battery capacity on board compared to opportunity charging systems the influence of the lifetime kilometres on the GHG emissions form production is even more significant.

In Figure 32, the influence of energy consumption of bus operation on GHG emissions in three selected countries. It is shown that the GHG emissions from operation increase in parallel with the increasing energy consumption of the bus. Nevertheless, in countries with a high share of renewable electricity this increase is less relevant than in countries using fossil based electricity. Anyway this analysis show that it is important to consider also the total primary energy demand in case where renewable electricity is used to identify the most energy efficient systems (see Figure 30)

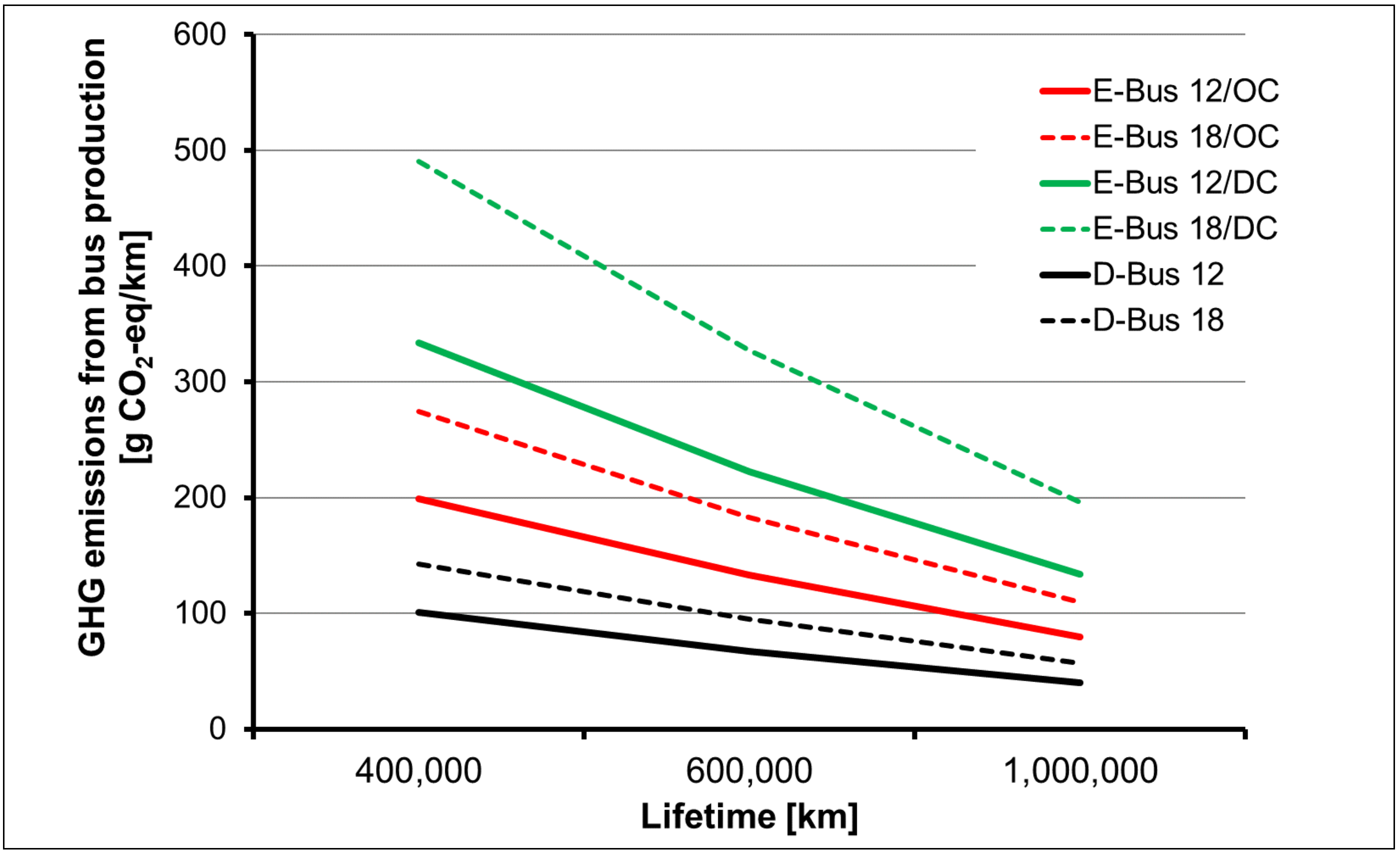


Figure 31: Influence of lifetime kilometres on GHG emissions of the bus production for bus systems with 12 m and 18 m buses

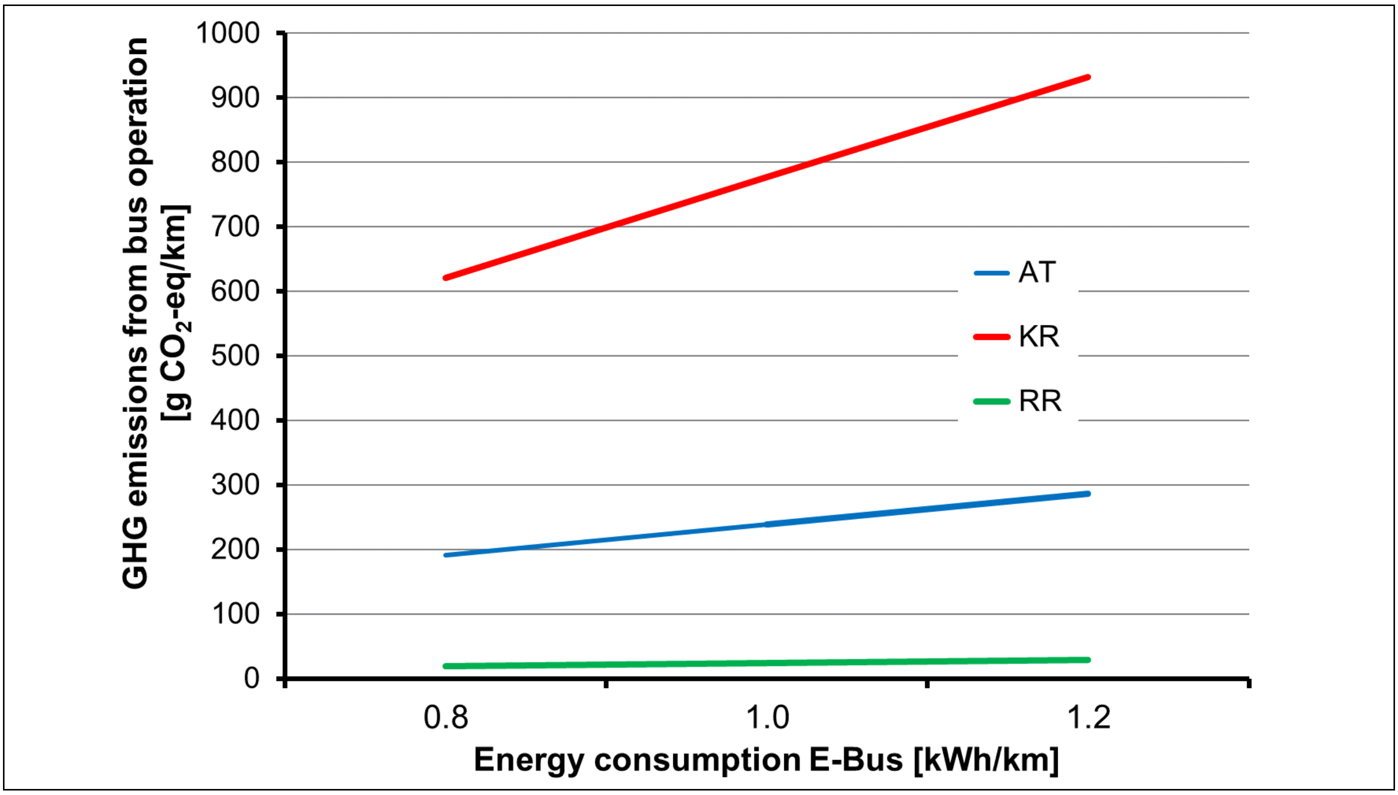


Figure 32: Influence of energy consumption of bus operation on GHG emissions in three selected countries

2.8.7 Conclusions

The environmental benefits of battery electric buses can be maximized, if additional renewable electricity is used and future battery production will be on high production capacity realising economy of scale efficiency potentials and using renewable energy. The current battery production mainly in Asia is associated with significant GHG emissions and fossil energy demand in the LCA of current bus systems. By using a high share of renewable electricity for battery electric buses, the total GHG emissions and fossil energy demand are lower than for diesel buses, and hydrogen buses. Battery electric buses have no local emissions (e.g. PM, NOx) and contribute to the improvement of air quality in cities.

2.9 Economic aspects

2.9.1 Methodology

The economic effects of e-bus systems must be calculated on the basis of total costs of ownership (TCO), whereas the investment costs for the buses, the charging infrastructure and the grid connection as well as the operating costs must be considered. The TCO of battery electric buses must be compared to diesel and hydrogen bus systems.

A TCO calculation is done for the charging systems and the total bus systems separately. The following cost are considered:

- Investment costs,
- Maintenance costs,
- Insurance cost, and
- Energy costs.

The TCO are calculated on an annual basis, where the annual capital costs from the investment cost are calculated using the lifetime and an interest rate of 3% for half of the investment.

The costs are calculated for the following bus systems:

- E-bus system with depot and opportunity charging,
- Hydrogen bus system using renewable hydrogen from electrolysis, and
- Diesel bus system.

The TCO are calculated for systems using 12 m buses in € per driven kilometre and due to the different passenger capacity in € per 1,000 p-km. The basic data for these bus systems derive from the cooperation in Task 33 and literature.

The costs are calculated for three typical situations to identify the most relevant influences:

- "Baseline": average - most expected parameters for the e-bus system,
- "Optimal": all parameters are in favour of the e-bus system, and
- "Sub-optimal": parameters are not in favour of the e-bus system.

2.9.2 Charging infrastructure

First the basic data are given and then the results of the cost assessment of the charging infrastructure are described.

2.9.2.1 Basic data

In Table 2 the basic data for cost assessment of the charging infrastructure for e-buses and hydrogen buses are shown.

Table 2: Basic data for cost assessment of charging infrastructure

		Depot charging			Opportunity charging			H2-production and filling station		
		baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal
Basic data										
Charging power	[kW]	38	30	60	387.5	350	500	4,323	4,167	4,792
Losses	[% output]	9%	8%	10%	11%	10%	15%	2%	1%	5%
Energy per bus	[kWh/(a*bus)]	87,500	90,000	80,000	73,750	75,000	70,000	186,250	195,000	160,000
Annual charging time	[h/(a*Bus)]	2,583	3,000	1,333	196	214	140	43	47	33
Charging time per filling	[h/Bus]	5.3	5.8	3.7	0.16	0.2	0.1	0.23	0.20	0.30
Max number of buses	[buses per day]	4.7	4.1	6.5	158	131	240	110	120	80
Energy per bus	[kWh/bus]	186	175	220	61	64	50	984	833	1437
	[kg_H2/bus]							30	25	43
Max full load hours	[h/a]	6,899	7,446	5,256	5,475	5,840	4,380	5,475	5,840	4,380
Number of charging per day	[#/d]	4	3	4	96	88	120	70	80	40
Annual charged energy	[kWh/a]	246,375	223,380	315,360	2,080,500	2,044,000	2,190,000	23,496,640	24,333,090	20,987,290
	[kg_H2/a]				-			704,906	730,000	629,625
Investment costs	[€]	37,500	30,000	60,000	312,500	250,000	500,000	6,705,666	6,441,606	7,497,847
Insurance	[% of investment]	1%	1%	2%	1%	1%	2%	1%	1%	2%
Maintenance	[% of investment]	4%	3%	5%	5%	4%	6%	6%	5%	8%
Electricity price	[€/kWh]	0.09	0.07	0.13	0.10	0.08	0.15	0.08	0.06	0.13
Efficiency electrolysis	[%]	0			0			63%	60%	70%
Lifetime	[a]	22.5	25	15	22.5	25	15	22.5	25	15
Annual electricity demand	[kWh/a]	269,703	242,804	350,400	2,347,451	2,271,111	2,576,471	38,613,557	40,964,798	31,559,835

2.9.2.2 Results

In Table 3, Figure 33 and Figure 34 the results form the cost assessment of the charging infrastructure are shown.

The results for the costs of the charging infrastructure show that the price for the electricity is dominating the total costs, whereas the costs (incl. investment) for the infrastructure are less relevant. Due to the lower energy efficiency the costs for supplying the hydrogen are higher than for electricity. Due to the higher investment costs of the opportunity charging systems compared to the depot charging system the costs for the supply of electricity by opportunity charging is higher than for depot charging.

In the baseline situation the costs for the energy supply for buses are:

- E-bus system with
  - depot charging 109 €/MWh,
  - opportunity charging 129 €/MWh,
- Hydrogen bus system using renewable hydrogen from electrolysis 163 €/MWh,
- Diesel bus system 100 €/MWh.

Under these assumptions, the supply of diesel still has the lowest costs. But, if it is possible to get a “good” price for electricity – especially for depot charging - the costs for supplying charging electricity to e-buses can be lower than diesel.

Table 3: Cost assessment of charging infrastructure

		Depot charging			Opportunity charging			H2-production and filling station		
		baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal
Annual costs										
Capital costs	[€/a]	2,463	1,650	4,900	20,521	13,750	40,833	418,797	354,288	612,324
Insurance	[€/a]	413	150	1,200	3,438	1,250	10,000	61,645	32,208	149,957
Maintenance	[€/a]	1,425	900	3,000	15,000	10,000	30,000	391,517	322,080	599,828
Electricity	[€/a]	24,135	16,996	45,552	232,884	181,689	386,471	2,869,111	2,457,888	4,102,779
Total	[€/a]	28,435	19,696	54,652	271,843	206,689	467,304	3,741,070	3,166,465	5,464,887
Spec. energy costs										
Charged energy	[€/kWh]	0.11	0.09	0.17	0.13	0.10	0.21	0.16	0.13	0.26
Charged hydrogen	[€/kg_H2]							5	4	9
Capital costs	[€/kWh]	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.01	0.03
Insurance	[€/kWh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Maintenance	[€/kWh]	0.01	0.00	0.01	0.01	0.00	0.01	0.02	0.01	0.03
Electricity	[€/kWh]	0.09	0.08	0.14	0.11	0.09	0.18	0.12	0.10	0.20
Total	[€/kWh]	0.11	0.09	0.17	0.13	0.10	0.21	0.16	0.13	0.26

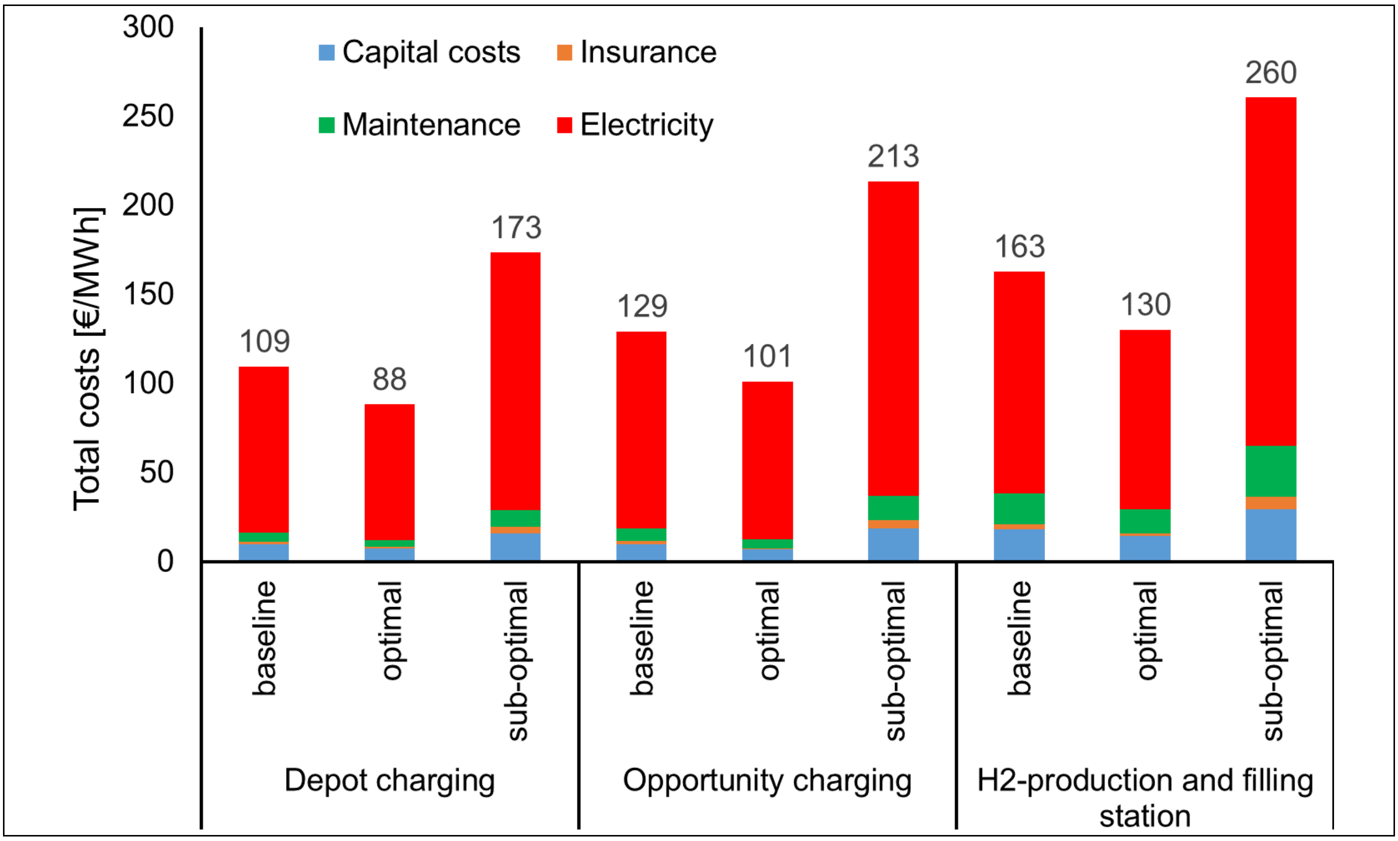


Figure 33: Costs of charging infrastructure and energy

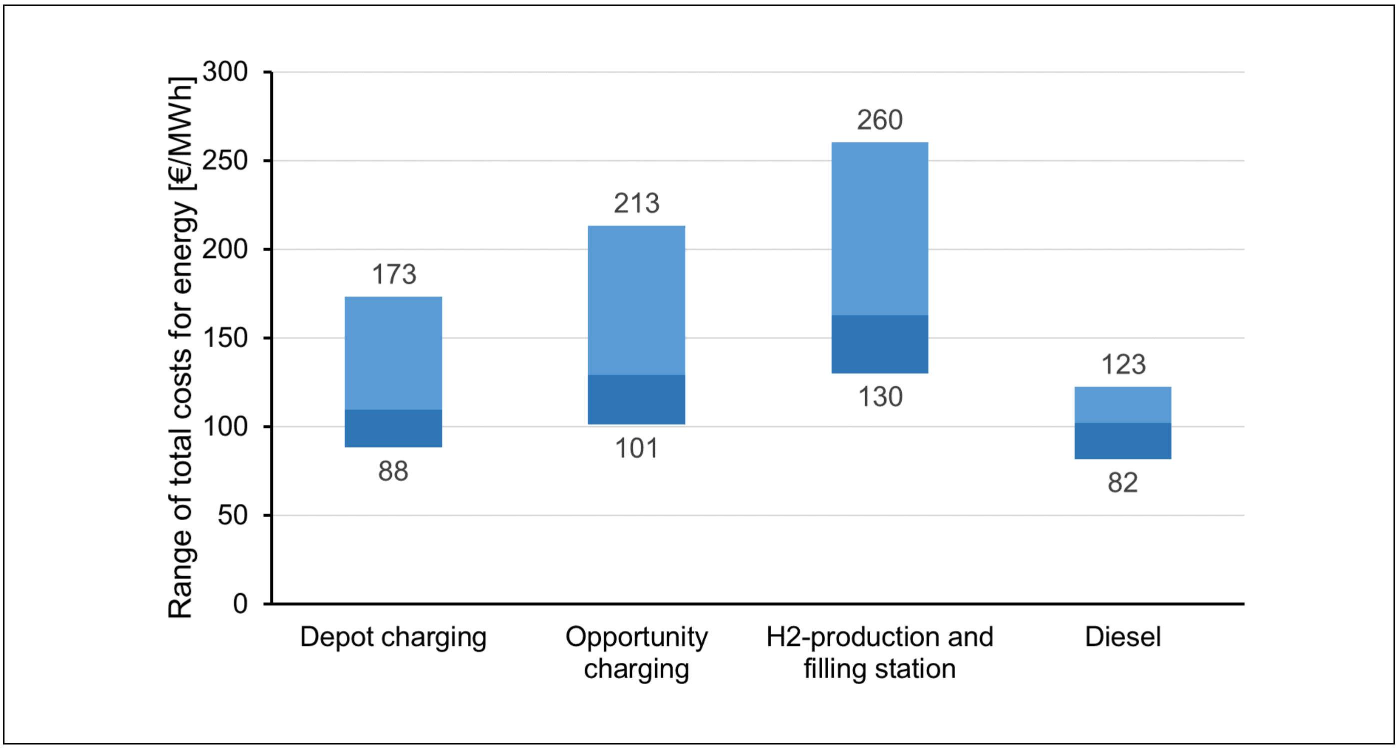


Figure 34: Ranges of costs for charging infrastructure and energy

2.9.3 Bus system

First the basic data are given and then the results of the cost assessment of the bus systems are described.

2.9.3.1 Basic data

In Table 4 the basic data for the cost assessment of bus systems are shown.

Table 4: Basic data for cost assessment of bus systems

		DC-BEB			OC-BEB			H2-FCB			D-Bus		
		baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal
Basic data													
Bus length	[m]	12.0	12	12	12	12	12	12	12	12	12	12	12
Traction energy consumption	[kWh/km]	1.3	1.2	1.6	1.1	1.0	1.4	2.8	2.6	3.2	3.3	3.0	4.0
Battery nominal capacity	[kWh]	287.5	250	400	170	160	200	10	8	15			
Max SoC	[-]	0.9	0.95	0.8	0.8	0.85	0.7	1.0	0.95	0.95			
Min SoC	[-]	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.1			
Reserve SoC	[-]	0.1	0.05	0.05	0.2	0.15	0.15	0.1	0.05	0.05			
SoC for auxilliaris	[-]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1			
Usable SoC	[-]	0.6	0.7	0.55	0.4	0.4	0.25	0.7	0.7	0.7			
Battery usable capacity/H2&Diesel Tank]	[kWh]	186	175	220	61	64	50	984	833	1,437	1,375	1,000	2,500
Tank (H2 and Diesel)	[kg_H2 and l_diesel]							30	25	43	140	102	255
Driving range/filling/charging	[km/charging/filling]	144	146	138	57	64	36	353	321	449	406	333	625
Capacity	[passengers/bus]	86	90	75	96	100	85	98	100	90	100	100	100
Lifetime bus	[a]	12	12	10	12	12	10	12	12	10	12	12	10
Lifetime battery	[a]	8	8	6	8	8	6						
Operation days	[d/a]	288	300	250	288	300	250	288	300	250	288	300	250
Daily kilometre	[km/d]	238	250	200	238	250	200	238	250	200	238	250	200
Annual kilometres	[km/a]	68,750	75,000	50,000	68,750	75,000	50,000	68,750	75,000	50,000	68,750	75,000	50,000
Lifetime kilometres	[km]	800,000	900,000	500,000	800,000	900,000	500,000	800,000	900,000	500,000	800,000	900,000	500,000
Annual energy	[kWh/a]	87,500	90,000	80,000	73,750	75,000	70,000	186,250	195,000	160,000	218,750	225,000	200,000
Investment costs bus (without battery)	[€]	270,000	260,000	300,000	270,000	260,000	300,000	575,000	500,000	800,000	230,000	220,000	260,000
Investment costs battery	[€/kWh]	513	450	700	513	450	700						
Investment costs battery	[€]	154,375	112,500	280,000	89,000	72,000	140,000						
Investment total bus	[€]	424,375	372,500	580,000	359,000	332,000	440,000	575,000	500,000	800,000	230,000	220,000	260,000
Insurance	[% of investment]	0.9%	0.5%	2.0%	0.9%	0.5%	2.0%	0.9%	0.5%	2.0%	0.9%	0.5%	2.0%
Maintenance	[% of investment]	2.3%	2.0%	3.0%	2.3%	2.0%	3.0%	3.5%	3.0%	5.0%	4.5%	4.0%	6.0%
Energy price	[€/kWh]	0.11	0.09	0.17	0.13	0.10	0.21	0.16	0.13	0.26	0.09	0.08	0.12

2.9.3.2 Results

The results of the costs assessment of the bus systems are shown in Table 5, Figure 35, Figure 36, Figure 37 and Figure 38.

The total costs of bus systems show that under baseline conditions the diesel bus systems has lower costs than systems with e-buses and hydrogen. The TCO of the hydrogen bus systems are higher than for the e-bus systems due to the higher costs for renewable hydrogen supply and the higher costs for investment of the bus. In general, the TCO for e-bus systems using opportunity charging are lower than for depot charging mainly due to the lower battery capacity, as the costs for battery have a significant influence on the TCO.

For all bus systems the most relevant costs are due to the capital costs. Due to the higher energy efficiency of the e-bus systems the costs for energy are significant lower than for hydrogen or diesel bus systems.

In the baseline situation the TCO of the different bus systems are:

- E-bus system with
  - depot charging 1.2 €/km,
  - opportunity charging 1.0 €/km,
- Hydrogen bus system using renewable hydrogen from electrolysis 1.9 €/km,
- Diesel bus system 0.9 €/km.

Considering the different passenger capacity, in the baseline situation the TCO of the different bus systems are per passenger-km:

- E-bus system with

    - depot charging 15 €/1,000 p-km,
    - opportunity charging 11 €/1,000 p-km,
- Hydrogen bus system using renewable hydrogen from electrolysis 20 €/1,000 p-km,
- Diesel bus system 8.7 €/1,000 p-km.

Under these assumptions, the diesel bus system still has the lowest costs. However, under optimal conditions the e-bus systems can be at about the same cost level as diesel buses.

The relative comparison of e-buses to diesel bus systems show for baseline situation the following cost differences:

- E-bus system with
    - depot charging 41%,
    - opportunity charging 15%,
- Hydrogen bus system using renewable hydrogen from electrolysis 115%.

The energy costs are for e-buses are about 50% lower than for diesel buses, but the capital costs are significantly higher for e-bus systems.

Table 5: Cost assessment of bus systems

Costs		DC-BEB			OC-BEB			H2-FCB			D-Bus		
		baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal	baseline	optimal	sub-optimal
Annual costs													
Capital costs bus (w/h) battery	[€/a]	27,800	25,567	34,500	27,800	25,567	34,500	59,875	49,167	92,000	23,700	21,633	29,900
Capital costs battery	[€/a]	24,529	15,750	50,867	13,918	10,080	25,433						
Insurance	[€/a]	4,297	1,863	11,600	3,445	1,660	8,800	5,875	2,500	16,000	2,125	1,100	5,200
Maintenance	[€/a]	9,938	7,450	17,400	8,280	6,640	13,200	21,250	15,000	40,000	10,500	8,800	15,600
Energy	[€/a]	9,418	7,936	13,864	9,422	7,584	14,937	29,447	25,375	41,662	19,500	18,000	24,000
Total	[€/a]	75,981	58,565	128,231	62,865	51,531	96,870	116,447	92,042	189,662	55,825	49,533	74,700
Kilometre costs													
Capital costs bus (w/h) battery	[€/km]	0.43	0.34	0.69	0.43	0.34	0.69	0.95	0.66	1.84	0.37	0.29	0.60
Capital costs battery	[€/km]	0.41	0.21	1.02	0.23	0.13	0.51	-	-	-	-	-	-
Capital total bus	[€/km]	0.84	0.55	1.71	0.66	0.48	1.20	0.95	0.66	1.84	0.37	0.29	0.60
Insurance	[€/km]	0.08	0.02	0.23	0.06	0.02	0.18	0.11	0.03	0.32	0.04	0.01	0.10
Maintenance	[€/km]	0.16	0.10	0.35	0.13	0.09	0.26	0.35	0.20	0.80	0.17	0.12	0.31
Energy	[€/km]	0.15	0.11	0.28	0.15	0.10	0.30	0.46	0.34	0.83	0.30	0.24	0.48
Total	[€/km]	1.23	0.78	2.56	1.00	0.69	1.94	1.87	1.23	3.79	0.87	0.66	1.49
					-								
Kilometre costs per passenger capacity													
Capital costs bus (w/h) battery	[€/1,000 P_km]	5.1	3.8	9.2	4.6	3.4	8.1	10.0	6.6	20.4	3.7	2.9	6.0
Capital costs battery	[€/1,000 P_km]	5.1	2.3	13.6	2.5	1.3	6.0	-	-	-	-	-	-
Capital total bus	[€/1,000 P_km]	10.3	6.1	22.8	7.1	4.8	14.1	10.0	6.6	20.4	3.7	2.9	6.0
Insurance	[€/1,000 P_km]	1.0	0.3	3.1	0.7	0.2	2.1	1.1	0.3	3.6	0.4	0.1	1.0
Maintenance	[€/1,000 P_km]	2.0	1.1	4.6	1.4	0.9	3.1	3.7	2.0	8.9	1.7	1.2	3.1
Energy	[€/1,000 P_km]	1.8	1.2	3.7	1.6	1.0	3.5	4.9	3.4	9.3	3.0	2.4	4.8
Total	[€/1,000 P_km]	15.1	8.7	34.2	10.9	6.9	22.8	19.7	12.3	42.1	8.7	6.6	14.9
					-								
Difference to diesel bus													
Capital costs bus (w/h) battery	[€/km]	0.06	0.05	0.09	0.06	0.05	0.09	0.59	0.37	1.24			
Capital costs battery	[€/km]	0.41	0.21	1.02	0.23	0.13	0.51	0.00	0.00	0.00			
Capital total bus	[€/km]	0.47	0.26	1.11	0.29	0.19	0.60	0.59	0.37	1.24			
Insurance	[€/km]	0.04	0.01	0.13	0.02	0.01	0.07	0.07	0.02	0.22			
Maintenance	[€/km]	0.00	-0.02	0.04	-0.03	-0.03	-0.05	0.18	0.08	0.49			
Energy	[€/km]	-0.15	-0.13	-0.20	-0.15	-0.14	-0.18	0.16	0.10	0.35			
Total	[€/km]	0.36	0.12	1.07	0.13	0.03	0.44	1.00	0.57	2.30			
Differences to diesel per km													
Capital costs bus (w/h) battery	[%]	17%	18%	15%	17%	18%	15%	160%	127%	208%			
Capital total bus	[%]	130%	91%	186%	79%	65%	100%	160%	127%	208%			
Insurance	[%]	107%	69%	123%	64%	51%	69%	184%	127%	208%			
Maintenance	[%]	-3%	-15%	12%	-20%	-25%	-15%	111%	70%	156%			
Energy	[%]	-50%	-56%	-42%	-50%	-58%	-38%	54%	41%	74%			
Total	[%]	41%	18%	72%	15%	4%	30%	115%	86%	154%			
Differences to diesel per P_km													
Capital costs bus (w/h) battery	[%]	41%	31%	54%	25%	18%	36%	174%	127%	242%			
Capital total bus	[%]	181%	112%	281%	94%	65%	136%	174%	127%	242%			
Insurance	[%]	165%	88%	197%	85%	51%	99%	208%	127%	242%			
Maintenance	[%]	20%	-6%	49%	-13%	-25%	0%	124%	70%	185%			
Energy	[%]	-40%	-51%	-23%	-45%	-58%	-27%	62%	41%	93%			
Total	[%]	73%	31%	129%	25%	4%	53%	127%	86%	182%			

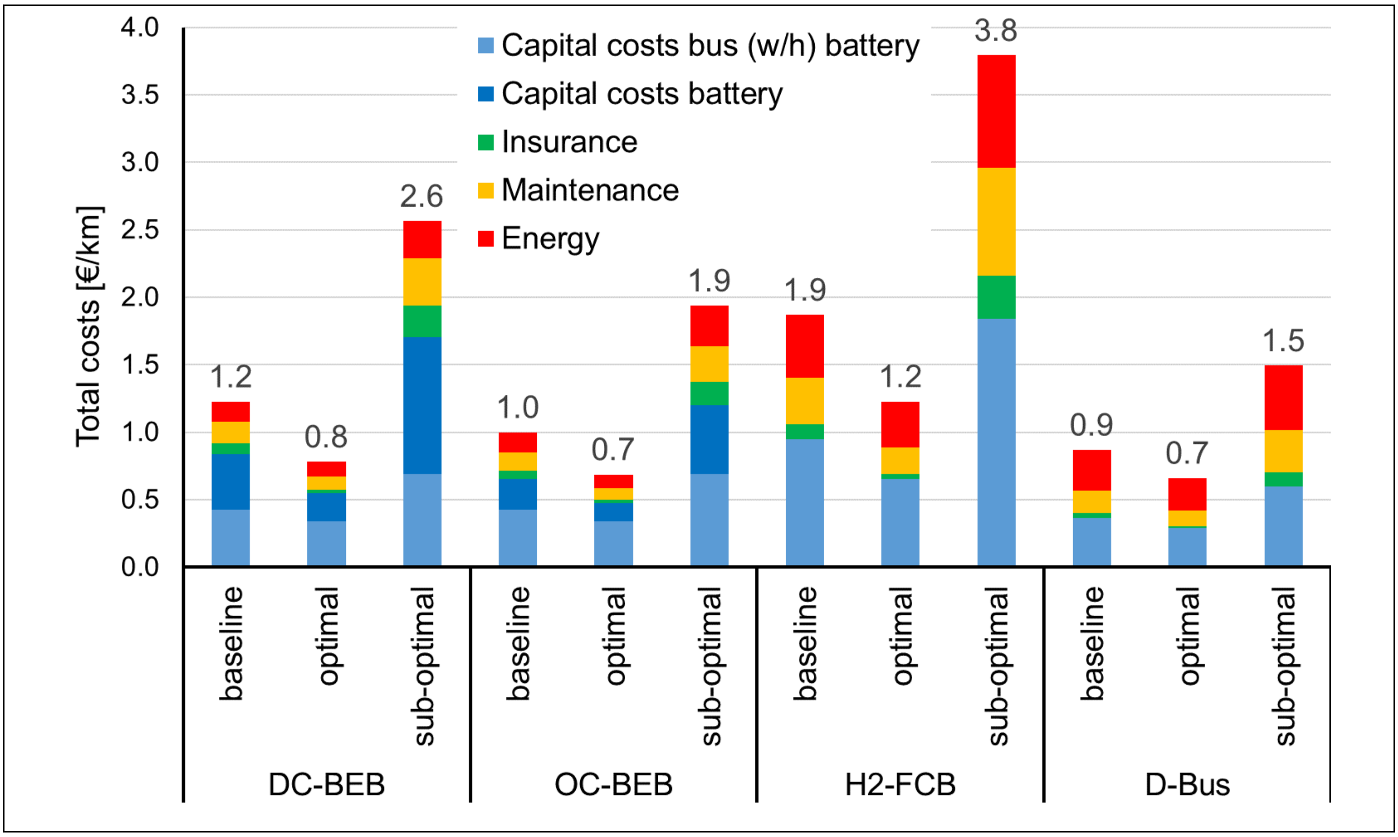


Figure 35: Costs per kilometre

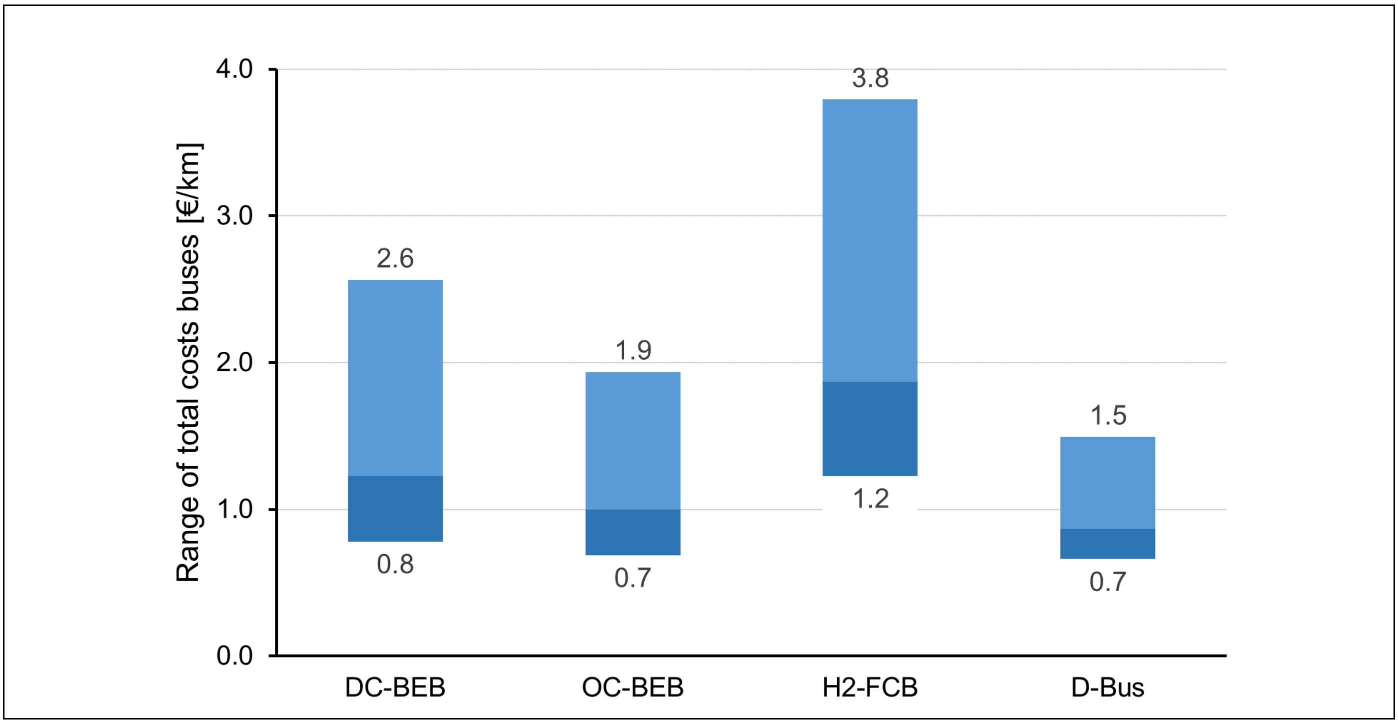


Figure 36: Ranges of costs per kilometre

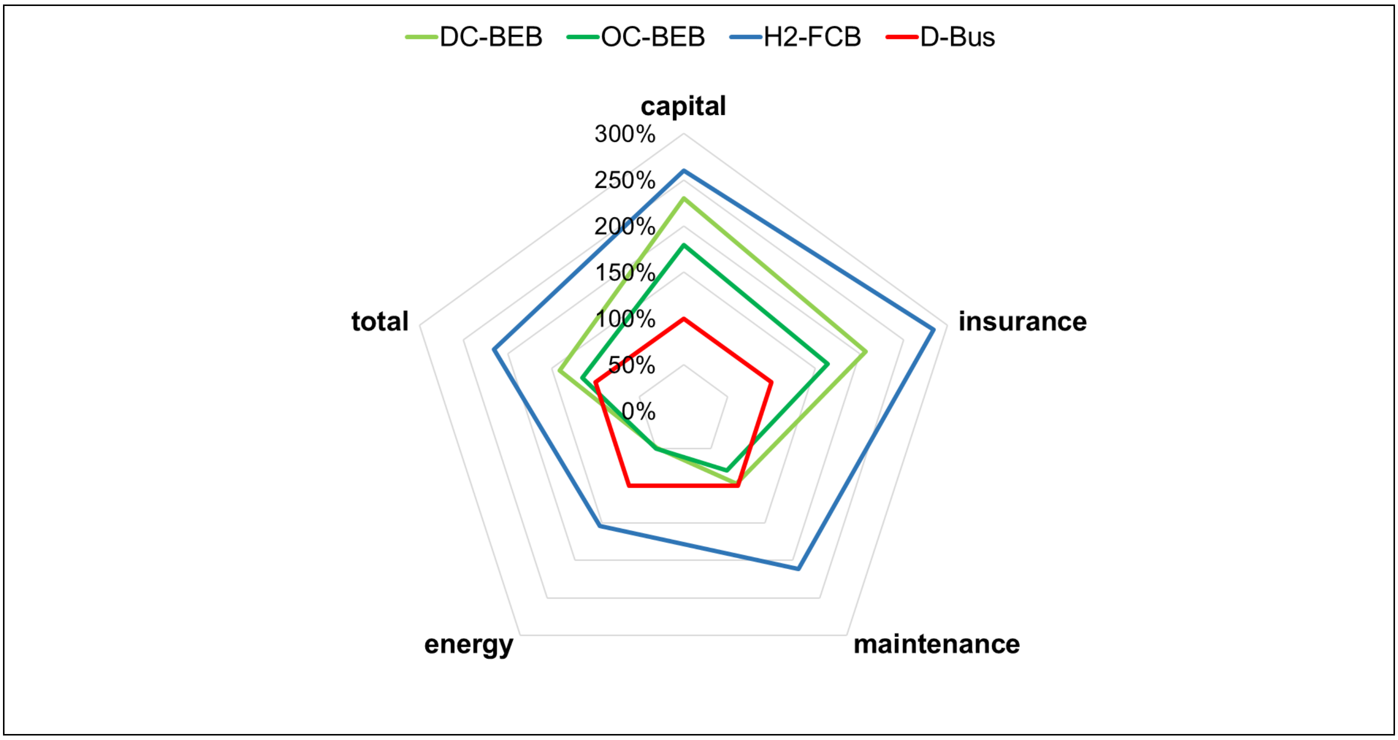


Figure 37: Costs per kilometre compared to diesel bus (Basis: 100%)

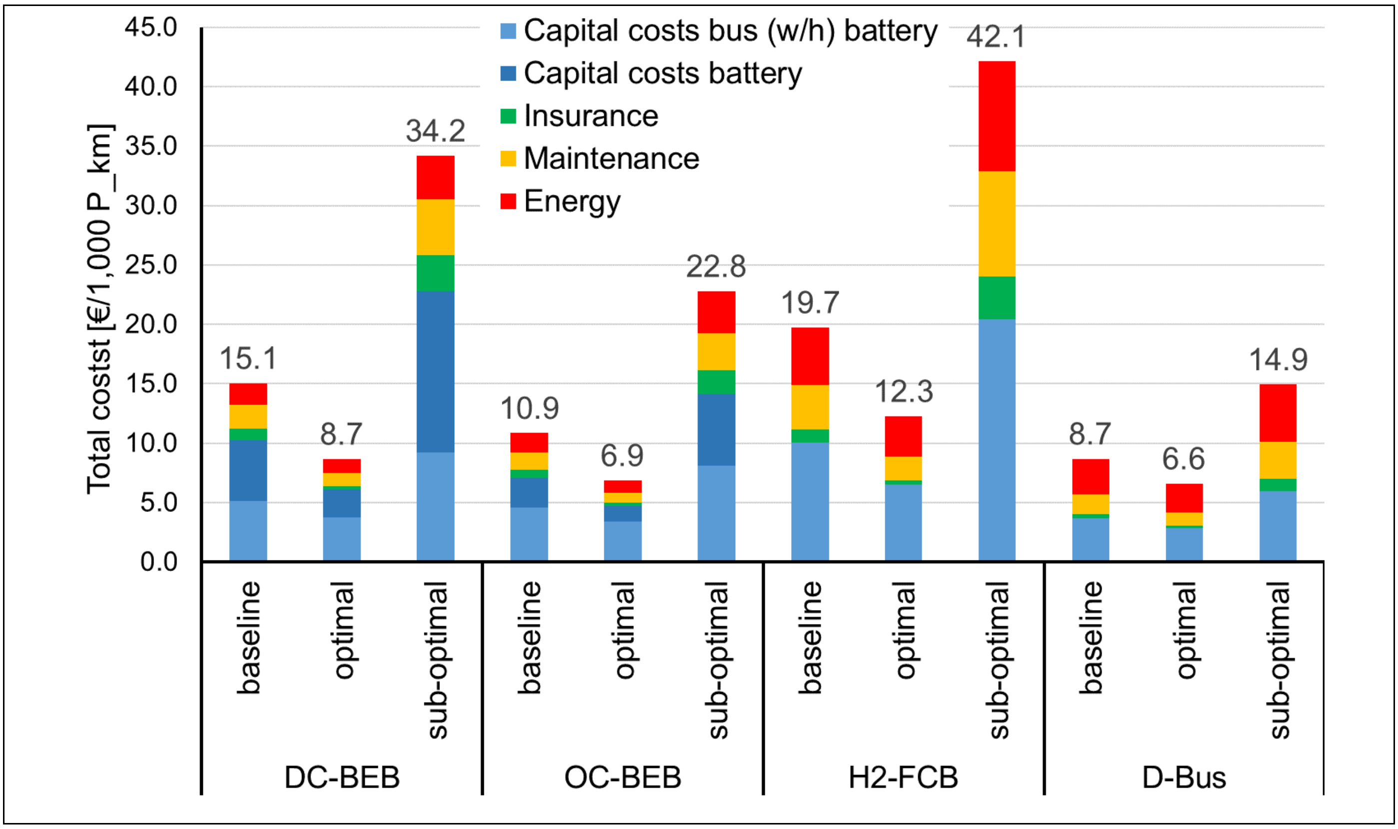


Figure 38: Costs per passenger kilometre

2.9.4 Conclusions

The economic effects must be calculated on the basis of total costs of ownership (TCO), whereas the investment costs for the buses, the charging infrastructure and the grid connection as well as the operating costs must be considered. The TCO of battery electric buses must be compared to current diesel buses. Currently the costs in €/km of e-buses are generally about 15 to 40% higher than for diesel buses. Additionally it must be considered, if more battery electric buses are needed to provide the same service as with diesel buses. In all cases, the hydrogen bus system has the highest TCO.

2.10 Comparison to other low- or zero-emission bus systems

Beside battery electric buses also hydrogen fuel cell bus, and synthetic biofuels and e-fuels (made from CO_2 and electricity) with an internal combustion engine (ICE) are future options for low- or zero-emissions bus systems. The application of biomethane and hydrotreated vegetable oil (HVO) is an option; in future the application of synthetic biofuels is also possible. Battery electric buses have a limited range by one charging, and can be applied in urban areas. If there is the need for longer range buses, hydrogen fuel cell buses and biofuel ICE buses might be a suitable alternative. In many countries hydrogen strategies are available, but the provision of green hydrogen is still very challenging. However, just as with the battery electric bus, further technical developments and significantly lower procurement costs for H_2 vehicles or tax incentives for the use of renewable fuels are needed here.

The Figure 39 shows a qualitative assessment based on expert judgements in Task 33 on the different bus technology systems compared to diesel covering the aspects of:

- Fuel/energy supply,
- Charging/fueling system, and
- Bus technology.

The qualitative assessment of the different aspects is done on three levels:

- Solved "+",
- Challenging "-", and
- Neutral "o".

Currently there is no "one fits all bus technology", but battery electric buses have strong advantages in terms of technology and short term introduction.

The hydrogen fuel cell bus, where hydrogen is used in a fuel cell to provide the electricity is also a local zero-emission bus. The main advantages of hydrogen fuel cell buses are the fast charging (about same time as a conventional diesel bus), the similar driving range as a diesel bus and the use of the waste heat from the fuel cell for heating in wintertime. The main disadvantages are currently the higher costs for the bus and the hydrogen infrastructure as well as the lower energy efficiency. In general, it is expected that battery electric buses are relevant for intercity bus lines in urban areas with limited driving range where fuel cell buses have the potential for long distance bus lines. The most relevant ongoing European hydrogen fuel cell demonstration project is JIVE - Joint Initiative for Hydrogen Vehicles across Europe (ongoing: https://www.fuelcellbuses.eu/projects/jive).

The main advantage of diesel buses are the low costs and the long driving range per filling, but their main disadvantages are the fossil energy demand and the high GHG emissions.

Biofuels and e-fuels for buses offer the same driving distance per filling as diesel buses, but they have significantly higher costs and lower energy efficiency. For synthetic biofuels, the main challenge is the supply of sustainable biomass and for e-fuels, the use of additional renewable electricity and a carbon neutral CO_2 source. Both technologies are not commercially implemented today.

Aspect	Battery electric bus	Hydrogen fuel cell bus	Synthetic biofuel ICE bus	E-fuel ICE bus	Diesel ICE bus
Fuel/energy supply					
State of technology	+	o	-	-	+
Renewable energy	+	o	o	-	-
Efficiency (WtT)	+	o	o	-	o
Investment costs	o	o	-	-	+
Integration in existing infrastructure	+	o	o	-	+
Charging/fueling system					
Integration in existing infrastructure	o	o	+	+	+
Driving distance per charging/fuel	-	o	+	+	+
Investment costs	o	-	+	+	+
Bus technology					
State of technology	+	o	+	+	+
Market availability	+	-	+	+	+
Efficiency (TtW)	+	o	-	-	-
Local emissions	+	+	-	-	-
Heating	o	+	+	+	+
Cooling	o	+	+	+	+
Investment costs	o	-	+	+	+
Operational costs	+	-	-	-	o

„+“ solved
„-“ challenging
„o“ neutral

Figure 39: Qualitative expert assessment of different bus system technologies

2.11 Dissemination activities

The following dissemination and exploitation activities in 2018 to 2020 took place:

- Poster at Market Place&paper: *Successful Demonstration of Battery Electric Buses Worldwide – A Game Changer in Urban Public Transport*, Transport Research Arena TRA 2018 in Wien, 16-19 April 2018
- Participation in *UITP-Training on Electric Buses*, 2-4 July 2018, Cologne, Germany
- Poster: *Challenges of Battery Electric Busses - Assessment of Demonstration Activities in IEA HEV Task 33*, A3PS Conference 2018 "Future Propulsion Systems: Different Regions - Different Strategies - Different Solutions, November, 12 - 13 2018, Vienna, Austria
- Participation in ZEB 2018 - Zero Emission Bus Conference, November 27&28, 2018, Cologne/Germany
- Abstract submitted (but not accepted): *E-Bus using Opportunity and Depot Charging in 8 Countries – GHG Emissions and Energy Saving Compared to Diesel Bus*, EVS32 – Electric Vehicle Symposium Lyon, France, May. 19 – 22, 2019
- Contribution to IEA HEV Annual Report 2018 "*Task 33 – Battery Electric Buses*" (http://www.ieahev.org/news/annual-reports/)
- Abstract submitted (but not accepted): *E-Bus using Opportunity and Depot Charging in 8 Countries – GHG Emissions and Energy Saving Compared to Diesel Bus*, EVS32 – Electric Vehicle Symposium Lyon, France, May. 19 – 22, 2019
- Participation in EVS 32, Electric Vehicle Symposium Lyon, France, May. 19 – 22, 2019
- Presentation *LCA of Battery Electric Buses and Comparison to Diesel and Fuel Cell Buses – What is the Functional Unit*, expert workshop Effects of EVs on Land Use – Resources – Waste incl. special topic: LCA of Autonomous Vehicles; June 13 – 14, 2019; Washington D.C., USA
- Key note presentation in Plenary session *Life Cycle Assessment of Electric Vehicle - Experiences of in the IEA Collaboration Program on Hybrid and Electric Vehicles (HEV)*, EV2019 - Electric Vehicles International Conference & Show, October 3-4, 2019 in Bucuresti, Romania
- Presentation *Current Status of Battery Electric Buses*, Austrian Expert Workshop "Future of Battery Electric Buses in Austria", October 8, 2019 in Graz, Austria
- Presentation *Die Lebenszyklusanalyse – Der Prüfstand für Technologien & Systeme einer zukunftsfähigen Mobilität*, Business Lounge - New Technologies in Life Cycle Analysis and Circular Economy Innovations des AC-Styria, 5.11.2019 Schloss Seggau/Leibnitz
- Documentation of expert workshop *Battery Electric Buses – Future Perspectives in Urban Environment*, November 20&21, 2019, Amsterdam and Eindhoven, The Netherlands
- Presentation *Environmental Aspects of Battery Electric Buses* and participation in the VCÖ Fachgespräch *Umweltbewertung mit Lebenszyklusanalyse*, Wien, December 12, 2019

- Participation in VDV BEB - Battery Electric Bus Conference, February 4&5, Berlin/Germany
- Presentation *Environmental Aspects of Battery Electric Buses* and participation in the Workshop *Lebenszyklusanalyse* von Erneuerbare Energie Österreich, Wien, December 12, 2019
- Presentation *Environmental Aspects of Battery Electric Buses* and participation in the H_2-round Table at ÖBB, February 26, 2020
- Contribution to IEA HEV Annual Report 2019 "*Task 33 – Battery Electric Buses*" (http://www.ieahev.org/news/annual-reports/)
- Presentation *Prüfstand Lebenszyklusanalyse: Klima- und Energiebilanz von Transportsystemen,* Symposium ZUKUNFT Gas-MOBILITÄT 2020, 11.-12. März 2020

2.12 Outlook

Based on the current trends the main challenges for battery electric buses are described and the R&D-demand is summarized.

2.12.1 Current trends

Focusing on current trends, it can be observed that the battery capacity of both opportunity charging in public space (OC) and depot charging (DC) buses is continuously increasing (Figure 40). Over the last 2 years, the increase is especially big in OC buses that increased from about 60 kWh up to about 200 kWh. E.g. in the Nordics, 12 m OC buses with battery capacity of over 200 kWh have already entered the daily service.

The manufacturers are forecasting further increases in battery performance. In urban use, battery electric buses with ranges of 150 to 250 km can already be used on about one third of regular routes. The next generation is expected in 2021, and could then cover more than 300 km at a stretch. Regarding DC buses, high-capacity solid-state batteries are entering the markets. For example, Mercedes Benz has started offering bus models with up to 440 kWh solid-state battery from 2020.

Different sizes on battery electric buses are now available, 12, 15 and 18 m buses from various brands. All major bus producers in Europe and in China are also producing battery electric 12 and 18 m buses, but also newcomers entered the market. Chinese manufactured buses are expected to enter the European markets. Currently, Chinese buses are not allowed to be sold to US, and since China has reduced the domestic incentives for battery electric buses, and as European countries have big pressure to decrease public transport related emissions, it is expected that the market amount of Chinese buses in the EU will probably increase significantly. The European manufacturers have to increase their production capacity significantly, to meet the expected strongly increasing market demand. Many European bus manufacturers invest or start to invest now in new production facilities, e.g. VDL. The Chinese buses have traditionally been DC buses; however, the new generation Chinese buses (esp. made by BYD) can also be OC buses with small/medium size battery.

For the design of new light weight battery electric buses, more aluminium and plastic components are developed and integrated in innovative new use concepts.

A massive rolling out phase has started, as projects are realised by rolling out 100 battery electric buses at once. Examples are:

- Helsinki aims for 30% of city buses electrified by 2025 (equals to about 400 battery electric buses),
- cities of Athens, Paris and Madrid, and country of Norway, plan to remove diesel vehicles by 2025,
- other cities and regions have announced plans to stop purchasing conventionally fuelled buses, including Copenhagen (in place since 2014), London (announced for 2020), Berlin (announced for 2020) or Oslo (announced for 2020),
- UITP (Union Internationale des Transports Publics) has stated that more than 13 public transport operators and authorities in further 18 European cities have a strategy up to 2025; by then, they are expected to have more than 6,100 battery electric buses in service, representing 43% of their total fleet of 14,000, and
- according to the Sustainable Bus Report (Sustainable Bus 2019) one source, the amount of battery electric buses in Western Europe (incl. Poland) raised to 1,687 in 2019 (from 548 in 2018).

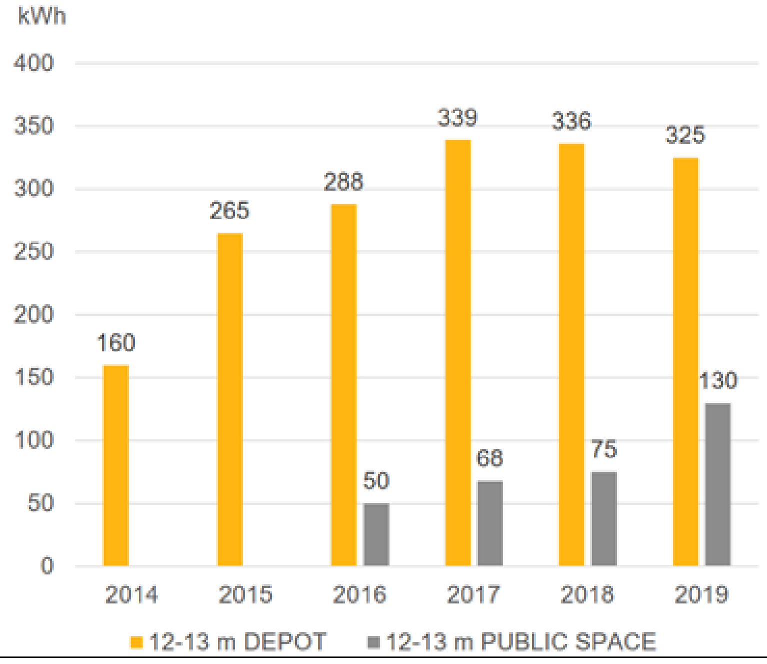


Figure 40: Development of average battery capacity of electric buses (Danchell 2019)

2.12.2 Main challenges for battery electric buses

The main challenges for battery electric buses derived from various demonstration activities are:

- High upfront cost,
- Further cost reduction of batteries with an increase of capacity,
- New challenging operations,
- New ways to procure,
- Vehicles and charging equipment,
- Operation services,
- Standardisation/interoperability, and
- Reinforcing cooperation between electricity sector and bus operation.

After the successful demonstration of battery electric buses the rollout phase for battery electric buses is going to come, where some cities e.g. Amsterdam, Eindhoven, Hamburg and Barcelona are taking the lead in Europe and Santiago de Chile in South American and Shenzhen in China.

Amsterdam and Eindhoven in the Netherlands are currently identified as the most advanced pilot cities in rolling out battery electric buses systems. In most of the cities, planing a massive roll out of electric buses and charging infrastructure, there is a strategy to have zero-emission public transport in coming years which give strong motivation for Public Transport Operators (PTO) to invest in battery electric systems. The factors for success are e.g.:

- PTO got to keep ticket revenue,
- One company responsible for the whole bus system: vehicles and charging system,
- Very high system availability (over 99%), and
- Good public reception: ”10% increase in average ridership”.

The results and lessons learned from daily e-bus operation so far are:

- Battery temperature is an important parameter in fast-charging and air-cooled batteries,
- Driver training is important, especially with e-bus operations,
- Extend limited range,
- E-buses are so quiet that tram bell needed to warn pedestrians,
- Choosing best charging strategies require open mind-set, and
- New heating strategies are being developed to improve fast-charging sessions.

The following main challenges are linked to the massive rolling out phase for battery electric buses:

- Increasing availability of battery electric buses and charges in daily operation (as less/no diesel buses are there for backup),
- Integration of fleet management,
- Energy and charging management to reduce cost and power capacity, and
- Grid stability and quality.

2.12.3 R&D issues

Focusing on the further development of battery electric buses, R&D needs are identified in the following fields:

- Fleet management,
- Heating and cooling systems and strategies,
- Inductive charging at stations/road,
- High power charging 1 MW and higher,
- Light weight vehicles, e.g. plastic and aluminium,
- Additional capacities to batteries for very quick charging,
- Bus to grid (B2G) concepts, applications and business models, and
- Integration of 2nd life batteries in depot charging system for peak shaving and additional renewable electricity storage.

In overall, this summarized to the main future challenge to develop advanced fleet management systems with for battery electric buses for optimal daily fleet operation.

3 Literature

Danchell 2019: Joachim Danchell: An overview of zero emission buses in the Nordic countries – by the end of 2019, link: https://zero.no/wp-content/uploads/2019/09/03.1-Overview-of-zero-emission-bus-in-the-nordic-Joachim-Danchell-Movia.pdf, 2019

IEA EV Outlook 2019: Global EV Outlook 2019 - Scaling-up the Transition to Electric Mobility, https://www.iea.org/reports/global-ev-outlook-2019

Kraaijvanger 2019: Bert Kraaijvanger: *E-Bus Fleets in the Netherlands: AML - One Year After Startup and EINDHOVEN - Nearly 3 years in Operation*, presentation at the IEA HEV Task 33 Workshop, Eindhoven, November 2019

Landerl 2016: Patrick Landerl: *Status and Future Perspectives of Electric Buses in Urban Public Transport*. Diplomarbeit an der TU-Graz. Graz, 2016

Sustainable Bus 2019: Sustainable Bus - Record year 2019. The big leap forward of e-bus market in Western Europe, link: http://www.sustainable-bus.com/news/record-year-2019-the-big-leap-forward-of-e-bus-market-in-western-europe/, 2019

tpg 2018: transports publics genevois: *First Experience of the Geneva's High Capacity eBus Line L23*, presentation at 1st Task 33 workshop, December 2018

4 Annex

4.1 Documentation of expert workshop on current status of battery electric buses

Battery Electric Buses

–

State of Technologies and Practical Experiences

Expert Workshop Summary

Time: December 11&12, 2018
Place: Espoo, Helsinki, Finland

Local organisers:

VTT

Joel Anttila, VTT, +358 40 836 4303, joel.anttila@vtt.fi

In cooperation with PROMOTING proEME ELECTRIC MOBILITY EUROPE and IEA-AMF

Introduction

Battery electric buses have the potential to substitute conventional diesel buses in public transportation services in cities. Recent technological developments and many demonstration projects worldwide, which are testing and demonstrating various types of electric buses, charging technologies and strategies as well as energy storage systems, might open a totally new zero-emission perspective for public bus services.

The Technology Collaboration Program (TCP) on "Hybrid and Electric Vehicle (HEV)" of the International Energy Agency (IEA) is operating the Task 33 "Battery Electric Buses" to analyse, discuss and assess the future of battery electric buses globally.

The objective of the Task 33 (2016 – 2019) is to analyse and assess the current state of technology & demonstration experiences of battery electric buses. This covers the storage technology e.g. battery or capacitor system, and the charging infrastructure, e.g. opportunity fast charging stations at bus stops and its optimal integration in an urban infrastructure, e.g. with synergies with trams, metro or trolley bus systems. The task work is based on an analysis of ongoing demonstration projects of battery electric buses worldwide. Based on this, the future perspectives and challenges for battery electric buses are analysed and described. This includes the identification of major challenges e.g. related to technologies, costs, public acceptance and the necessary R&D demand. Finally, the key aspects for a successful broad introduction of battery electric buses and the necessary framework conditions are concluded.

Aims of the workshop

The aim of the expert workshop of Task 33 is to analyse, discuss and assess the current state of technology of battery electric bus systems.

The main topics of the workshop are:

1. Charging technologies and strategies
2. Bus technologies
3. Environmental and economic assessment
4. Experiences worldwide.

To gain conclusion in group work on

1. State of technology of battery electric buses
2. State of technology of charging technologies and concepts
3. Identification of key aspects for battery electric bus systems

The workshop is structured in the following sessions:

1. Keynote
2. Experiences in Europe, Asia and America
3. Assessment
4. Group work
5. Visit of Helsinki Battery Bus System

SUMMARY

The system of battery electric buses in combination with adequate charging infrastructure has been demonstrated globally in various European, Asian and American countries.

The workshop covers projects within the last 4 years; the main results of the workshop are covering the following issues:

- European projects
- Current experiences
- Lessons learnt from demonstration
- Main charging strategies
- Manufacturers of battery electric buses
- Interoperability
- Heating and cooling
- Key performance indicators
- Additional indicators
- Hydrogen fuel cell bus
- Environmental effects
- Economic effects
- Main challenges for battery electric buses
- Strategy to have Zero-Emission public transport
- Rolling out phase
- Pilot Cities for rolling out battery electric buses
- Case City “Eindhoven”

In Europe the following **European projects** are most relevant in demonstrating and preparing the broad market rollout for battery electric buses in cities:

- ZeEUS – Zero Emission Urban Bus Systems (finished: http://zeeus.eu/),
- ELIPTIC – Electrification of Public Transport in Cities (finished: http://www.eliptic-project.eu/) and
- ASSURED - boosting the electrification of urban commercial vehicles and their integration with high power fast charging infrastructure, evaluating several infrastructures in different cities across Europe (ongoing: https://assured-project.eu)

Currently there are three **main charging strategies** under demonstration and testing, whereas combinations are realised:

- Overnight (slow) charging in the depot, which requires buses with a high battery capacity (> 300 kWh)
- Opportunity fast charging at final stops and

- Opportunity fast charging at intermediate stops, which needs the lowest battery capacity (< 100 kWh) but a highly developed charging infrastructure with adequate grid connection.

Current experiences and assessment show no clear advantages or favour for one of these three charging strategies, as it totally depends on the local conditions of the line served and available infrastructure (e.g. bus depot, public space available for charging, battery costs and their future development, grid connection). In general, it can be observed that there are more demonstration projects with opportunity charging at final or intermediate stops. In some cities also battery electric buses using a range extender with hydrogen and fuel cells are under consideration and tested to enlarge the driving range and limit the battery capacity.

The main **lessons learnt from demonstration** projects are

- Gradual vehicle introduction depending on knowledge of public transport operator (PTO) and technology chosen to ensure service operation
- Paradigm shift: from vehicle procurement to system procurement
- Early stakeholder involvement in the planning, joint feasibility study
- IT supporting fleet monitoring to optimise operation
- Identification of main elements needed for “local” LCC (Life cycle cost) model
- Integrating e-bus services into the overall city transport decarbonisation/defossilisation strategy.

Some of the most relevant **manufacturers of battery electric buses** are: VDL, Van Hool, Solaris, BYD, Linkker, IRIZAR, SAFRA, VOLVO, Wrightbus, DAIMLER.

The **interoperability** of future battery electric buses (of different brands) and charging infrastructure (of different suppliers) is essential for the future success and for taking the right investment decision. In 2020 an ISO Standard is expected which will guarantee the interoperability. The standard for inductive and wireless charging of electric buses should be agreed upon late 2020.

Using the energy of the battery for **heating and cooling** might reduce the driving range significantly, therefore also diesel heaters are used as an interim solution for the transition period when electrifying bus fleets. New technologies are under development and tested, e.g. heat pumps.

The **key performance indicators** for battery electric bus systems are

- Operating costs and energy consumption
  - Energy costs for driving (€/km): including electricity (from grid) and heater fuel
  - Operational driving distance (%/km): operational (on route) distance driven compared to the planned bus circulation
  - Total electricity consumption (kWh/km): total charged external energy (from charger) / kilometres driven (both on route and total km’s)
- Charging system performance

- Time required positioning the bus at the charger (s): time to manoeuvre the bus to the charger. From arrival at the charger proximity to the point when the driver initiates the charging.
- Total charging time (s): charging duration per sequence step from the charging start command to bus being ready to leave.
- Charging node utilization (%): time when the charging position is occupied / time available. Time occupied includes the active and dead times.

- System performance
  - Depart on schedule (%): percentage of departures left on schedule
  - Availability of the vehicles (%): percentage of the time that the vehicles have been available for service
  - Availability of the infrastructure (%): percentage of time when charging service is available / calendar time

As **additional indicators** the following are relevant:

- Powertrain electricity consumption (kWh/km): inverter consumed electricity / kilometres driven (on route)
- Heating electricity consumption (kWh/km): electricity consumed by the HVAC system (both on route and total)
- Auxiliaries electricity consumption (kWh/km): electricity consumed by other electric auxiliaries, such as power steering, air compressor and DC/DC (on route)
- Fuel consumption (l/h): fuel heater fuel consumption vs. temperature
- Charging efficiency (%): electricity from the grid / Electricity into the battery
- Dead time in charging (%): Dead time in charging / total charging time
- Battery efficiency (%): electricity out from the battery / Electricity into the battery
- Total system energy efficiency (%): electricity out from the battery / Electricity from the grid
- Minimum SoC in operation: lowest battery state of charge in operation
- Average delta SoC in operation: estimate from operational data
- Battery health, SOH (%): Percentage of the remaining battery capacity versus battery nominal capacity

A **hydrogen fuel cell bus**, where hydrogen is used in a fuel cell to provide the electricity is also a local zero-emission bus. The main advantage of hydrogen fuel cell buses are the fast charging (about same time as a conventional diesel bus), the similar driving range as a diesel bus and the use of the waste heat from the fuel cell for heating in wintertime. The main disadvantages are currently the higher costs for the bus and the hydrogen infrastructure as well as the lower energy efficiency. In general, it is expected that battery electric buses are relevant for intercity bus lines in urban areas with limited driving range where fuel cell buses have the potential for long distance bus lines. The most relevant ongoing European hydrogen fuel cell demonstration project is JIVE - Joint Initiative for Hydrogen Vehicles across Europe (ongoing: https://www.fuelcellbuses.eu/projects/jive).

The **environmental effects** of battery electric buses can only be assessed on the basis of Life Cycle Assessment taking the entire life cycle into account – production of the bus (incl. battery) and the infrastructure, operation of the bus including the supply of the electricity and the end of life management of the facilities, e.g. recycling, reuse. The environmental effects deriving from LCA must be compared to a diesel bus (and hydrogen fuel cell bus if of interest). The environmental benefits of battery electric buses can be maximised if additional renewable electricity is used and future battery production will be on high production capacity realising economy of scale efficiency potentials and using renewable energy. The current battery production mainly in Asia is associated with significant GHG emissions and fossil energy demand in the LCA of current bus systems. By using a high share of renewable electricity for battery electric buses the total GHG emissions and fossil energy demand are significantly lower than diesel buses. In addition, battery electric buses have no local emissions (e.g. PM, NOx) and contribute to the improvement of air quality in cities.

The **economic effects** must be calculated on the bases of total costs of ownership (TCO), whereas the investment costs for the buses, the charging infrastructure and the grid connection as well as the operating costs must be considered. The TCO of battery electric buses must be compared to current diesel buses. Currently the costs in €/km of diesel buses are generally about 20% lower than of battery electric buses. Additionally it must be considered, if more battery electric buses are needed to provide the same service as with diesel buses. For opportunity charging possibly more time for the driver is needed, which might increase costs for the driver.

The **main challenges for battery electric buses** derived from various demonstration activities are

- High upfront cost
- New challenging operations
- New ways to procure
    - Vehicles & charging equipment
    - Operation services
- Standardisation/interoperability and
- Reinforcing cooperation between electricity sector and bus operation

After the successful demonstration of battery electric buses the **rollout phase** for battery electric buses is going to come, where some cities e.g. Amsterdam, Eindhoven, Hamburg and Barcelona are taking the lead in Europe and Santiago de Chile in South American and Shenzhen in China.

Amsterdam and Eindhoven in The Netherlands are identified as the most advanced **pilot cities** in rolling out battery electric buses systems. In most of these cities there is a **strategy to have zero-emission public transport** in coming years that give strong motivation for Public Transport Operators (PTO) to invest in battery electric buses.

The main characteristics of the battery bus system in **Case City "Eindhoven"** are:

- 43 electric buses:

    - 18m VDL Citea SLFA-E181
    - NMC batteries with 180 kWh
- Opportunity charging
    - 300 kW
    - Opportunity charging at bus depot: ~40 minute charge time
- Overnight charging
    - 30 kW
    - 4 to 5 hours
- Operational conditions
    - Line numbers: 400, 401, 402, 403, 404, 405, 406 and 407
    - Topology: City centre and suburban
    - Topography: Flat
    - Length: 4.4 – 12.3 km
    - Average commercial speed: 18.5 – 27.5 km/h
    - Total daily hours of operation: 20 h
    - Total km driven per day per vehicle: avg. 200 km, max. 300 km
    - Average number of passengers per day: 11 500 passengers per line
- Factors for success
    - PTO got to keep ticket revenue
    - One company responsible for the whole bus system: Vehicles and charging system
    - Very high system availability (over 99%)
    - Good public reception: ”10% increase in average ridership”
- Results and lessons learned
    - Battery temperature is an important parameter in fast-charging and air-cooled batteries
    - Driver training is important, especially with e-bus operations
    - Extend limited range
    - E-buses are so quiet that tram bell needed to warn pedestrians
    - Choosing best charging strategies require open mind-set
    - New heating strategies are being developed to improve fast-charging sessions
- Future plans
    - Development phase 2: adding 65 E-Buses during period 2019 - 2021
    - Development phase 3: adding 65 E-Buses during period 2022 - 2024
    - Charging facility expansion to further locations

PROGRAMM

Tuesday December 11, 2018

9:30 Welcome addresses

VTT (N.N.)

IEA HEV (Gerfried Jungmeier)

IEA AMF (Marcela Castillo Reyes)

proEME (Deniz Oezcan)

9:45 Introduction - Aims of the Workshop

10:00 – 10:15 IEA HEV Task 33 "**Battery Electric Buses**" (Gerfried Jungmeier, JOANNEUM RESEARCH, A)

KEY NOTES

Chair: N.N.

10:15 – 10:45 **First Experience of the Geneva's High Capacity eBus Line L23**, Olivier Auge, TPG - Transport Publics Genevois, Switzerland

10:45 – 11:15 **Practical Experiences with Electric Buses in Helsinki**, Reijo Mäkinen, Helsinki Regional Transport

11:15 – 11:45 **Status and Perspective for Electric Buses – A Research View**, Mikko Pihlatie, VTT, Finland

11:45 – 12:30 Discussion

LUNCH

EXPERIENCES IN EUROPE, ASIA AND AMERICA

Chair: N.N.

13:30 – 14:00 **Challenges of Battery Electric Buses in Santiago**, Marcela Castillo, Molina Center for Energy and the Environment and IEA AMF Annex 53 „Sustainable Bus Systems", Chile

14:00 – 14:30 **Towards a Sustainable and Efficient Urban Mobility System in Uruguay**, Martín Piñeyro, GEF – PNUD – MIEM – MVOTMA, Uruguay

14:30 – 15:00 **Modelling of Routes and Charging Concepts for Electric Buses**, Joel Anttila, VTT, Finland

15:00 – 15:20 **Experiences with Battery Electric Buses in Barcelona**, Nick Chapman, IREC, Spain

15:20 – 15:40 **Experiences with Battery Electric Buses on Asian Roads – Example Republic of Korea**, Ock Taeck Lim, University of Ulsan, Republic of Korea - *cancelled*

15:40 – 16:00 Discussion

BREAK

SITE VISIT

Visit and test ride of local battery electric buses and charging systems

DINNER.

PROGRAMM

Wednesday December 12, 2018

ASSESSMENT

Chair: N.N.

.9:00 – 9:30 **Comparing Battery Electric Buses and Hydrogen Fuel Cell Buses**, Heinrich Klingenberg, hySOLUTIONS GmbH, Germany

9:30 – 10:00 **Environmental Aspects of Battery Electric and Diesel Buses**, Gerfried Jungmeier, JOANNEUM RESEARCH, Austria

10:00 – 10:30 **Economic Aspects of Battery Electric Buses**, Johannes Pagenkopf, DLR/pro-EME, Germany

10:30 – 11:00 Discussion

BREAK

11:30 – 13:00 **Group work** on Identification of key aspects for battery electric bus systems

LUNCH

14:00 – 15:00 Presentation and discussion of group work

15:00 – 15:30 **Summary**, conclusions and next steps

END of WORKSHOP

16:00 – 17:30 Task 30 business meeting (members only)

Task 30 DINNER

Contact

For further information please contact

Gerfried Jungmeier
Operating Agent of IEA HEV Task 33 „Battery Electric Buses"

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Task 33 "Battery Electric Buses"

Members: Austria, Canada, Finland Germany, Spain, South Korea

The objective of the Task 33 (2016 – 2019) is to analyse and assess the current state of technology & demonstration experiences of battery electric buses. This covers on one hand the bus technology e.g. battery or capacitor system, and on the other hand the charging infrastructure, e.g. fast charging stations at the bus stop and its optimal integration in an urban infrastructure, e.g. synergies with trams, metro or trolley bus systems. The task work is done based on an analysis of ongoing demonstration projects of battery electric buses worldwide. Based on this the future perspectives and challenges for battery electric buses are analyses and described. This includes the identification of major challenges e.g. technology, costs, public acceptance and the necessary R&D demand. Finally the key aspects for a successful broad introduction of battery electric buses and the necessary frame work conditions are concluded.

The work is done in a close cooperation of the relevant stakeholder from the three focus groups:

- Provider of public transportation services,
- System and technology providers
- Research institutions

The results are continuously documented and disseminated via presentations, workshops, conference contributions and publications.

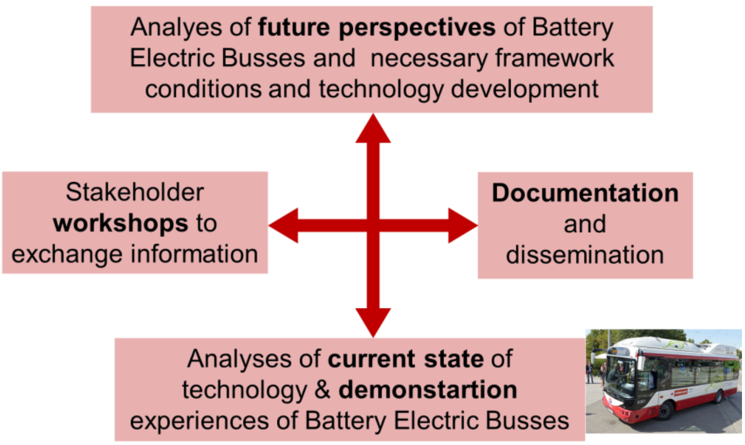

Figure 2: Objectives

The major activities are

- Identify &analyse state of technology and systems of battery electric buses
- Collect and document „International Success Stories“ in a common format
- Give overview of systems &technology providers with characteristic data
- Stakeholder involvement in 2 - 3 Workshops in combination with site visit
- Analyse combination of trolley and battery bus systems
- Integration and use of existing infrastructure of trams, trolleys and metro
- Identify success factors, e.g. size of bus, distances between bus stops
- Define loading strategies
- Analyse sustainability issues – economic, environmental &social aspects
- Identify R&D demand
- Conclude and summarize future perspectives
- Publish IEA HEV glossy Brochure of results
- Presentations and contribution at conferences

The most important activity of the working method is the organization of workshops in different member countries to involve the stakeholders in the value chain of battery electric buses, e.g. provider of public transportation services, system and technology provider, research institutions. The organization of workshops with participation from industry, research organizations, technology policy experts and governmental institutions provides an international basis for the exchange of information on the relevant activities. The focus of the expert workshops is to analyse, discuss and document the

1 State of technology for battery electric buses
2 Future perspectives of battery electric buses

The workshops are combined with a site visit to an ongoing demonstration of battery electric buses in daily life application.

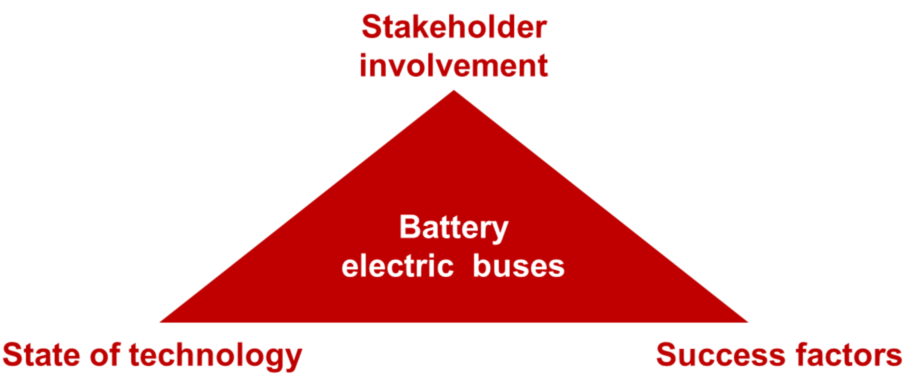

Figure 3: Working method

Operating Agents

For further information, please contact the Task 33 Operating Agent:

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The Work of JOANNEUM RESEARCH is financed by Austrian Klima + Energie Fonds

http://www.ieahev.org/tas

4.2 Documentation of expert workshop on future perspectives of battery electric buses

Battery Electric Buses

–

Future Perspectives

Expert Workshop Documentation

Time: November 20&21, 2019

Place: Eindhoven, The Netherlands

Local organisers:

Gerfried Jungmeier, JOANNEUM RESEARCH, +43 664 602 876 7630, gerfried.jungmeier@joanneum.at

In cooperation with PROMOTING proEME ELECTRIC MOBILITY EUROPE and

Content

Introduction

Battery electric buses have the potential to substitute conventional diesel buses in public transportation services in cities. Recent technological developments and many demonstration projects worldwide, which are testing and demonstrating various types of electric buses, charging methods and strategies as well as energy storage systems, might open a totally new zero-emission perspective for bus services.

The Technology Collaboration Program (TCP) on “Hybrid and Electric Vehicle (HEV)” of the International Energy Agency (IEA) is operating the Task 33 “Battery Electric Buses” to analyse, discuss and assess the future of for battery electric buses globally.

The objective of the Task 33 (2016 – 2019) is to analyse and assess the future perspectives mobility systems with battery electric buses. This covers the bus technology e.g. battery or capacitor system, and the charging infrastructure, e.g. fast charging stations at the bus stop and its optimal integration in an urban infrastructure, e.g. synergies with trams, metro or trolley bus and hydrogen systems. The task work is done based on an analysis of ongoing demonstration projects of battery electric buses worldwide. Based on this the future perspectives and challenges for battery electric buses are analysed and described in comparison to hydrogen buses. This includes the identification of major challenges e.g. technology, costs, public acceptance and the necessary R&D demand. Finally, the key aspects for a successful broad introduction of battery electric buses and the necessary framework conditions are concluded.

Aims of the workshop

The aim of the expert workshop of Task 33 is to analyse, discuss and assess the future perspectives for battery electric bus systems in an urban environment.

The main topics of the workshop are:

1. Charging technologies and strategies
2. Bus technologies
3. Environmental and economic assessment
4. Experiences around the globe
5. Framework conditions
6. Main challenges and open issues e.g. R&D demand
7. Site visits of battery electric buses in daily operation in Amsterdam and Eindhoven

To gain conclusion in group work on

1. Future perspectives for battery electric buses
2. Future perspectives for charging technologies and concepts
3. Identification of key aspects for battery electric bus systems in an urban environment

SUMMARY

The key aspects for summarizing the workshop are

- Key drivers for battery electric buses
- Clean Vehicles Directive
- Charging systems
- Fleet management
- Performance indicators
- Other low- or zero-emission bus systems
- Environmental aspects
- Current trends
- R&D issues

These aspects are described in the following.

Key drivers for battery electric buses

The system of battery electric buses in combination with adequate charging infrastructure has been demonstrated globally in various European, Asian and American countries. Within the workshop, the different main drivers for the now starting broad market introduction of battery electric buses were identified, these are:

- climate protection and decarbonisation of the transportation sector,
- diminishing local air pollution,
- expanding the supply of more public transport services for climate friendly mobility, to motivate more people to use public transport especially also in the countryside,
- establishing new bus lines are the most rapid short-term option to increase public transport services compared to installing new tram and metro lines,
- from supply to demand orientation in public transport, new public mobility services are necessary,
- initiate first systems for a so called “hybrid public transport” in future which is the integration of autonomous vehicles in public transport,
- the European Green Vehicle Directive – further information see below,
- “Green deal” in Europe: significant GHG reduction until 2030 and climate neutrality in 2050,
- innovation of new vehicle and propulsion systems,
- development of new value chains and business models,
- technology and industry development for global market,
- digitalization and mobility as a service (MaaS),
- increasing renewable electricity generation,
- sector coupling: excess renewable power,
- circular economy, and
- the expectation that 2020 – 2030 will be the “century of battery electric buses in urban environment”.

Clean Vehicles Directive

In Europe the Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles[4] now pushes the market introduction of clean vehicles significantly. The "Clean Vehicles Directive" promotes clean mobility solutions in public procurement tenders, providing a solid boost to the demand and further deployment of low- and zero-emission vehicles. This Directive defines "clean vehicles" and sets national targets for their public procurement. It applies to different means of public procurement, including purchase, lease, rent and relevant services contracts. The Directive needs to be transposed into national law in EU member countries by 2 August 2021.[5]

The Directive defines a "clean vehicle" as follows:

- Clean light-duty vehicle: any car or van meeting the following emission thresholds:
    - until 31 December 2025: no more than 50g/km CO_2 and up to 80% of applicable real driving emission (RDE) limits for NOx and PM;
    - from 1 January 2026: only zero-emission vehicles.
- Clean heavy-duty vehicle: any truck or bus using one of the following alternative fuels: hydrogen, battery electric (including plug-in hybrids), natural gas (both CNG and LNG, including biomethane), liquid biofuels, synthetic and paraffinic fuels, LPG.[2]

The Directive also sets a separate definition for "zero-emission heavy-duty vehicles" (clean vehicle without an internal combustion engine, or with an internal combustion engine that emits less than 1 g CO_2/kWh), as a sub-category of clean heavy-duty vehicles.

The Directive sets out mandatory minimum procurement targets in each Member State as national targets for clean light-duty vehicles, trucks and buses. On buses, 50% of the minimum target for the share of clean buses has to be fulfilled by procuring zero-emission buses. The national targets are set for two periods and are for buses:

- for 2021 -2025 between 24 – 45%, and
- for 2026 – 2030 between 33 – 65%.

Charging systems

The charging systems are a very essential part, while talking about battery electric buses. Harmonized charging systems are necessary for fast and/or opportunity charging on the route or in the depot. Below Figure 1 shows a qualitative assessment based on experts on the two different charging systems – opportunity charging (OC) and depot charging (DC), looking on charging technology, operation and vehicles. Currently there is no "one fits all charging solution" as the site specific framework conditions have to be considered. For depot charging (110 kV with 25 MVA operation) of a big fleet of battery electric buses the grid connection is a challenge; grid availability is quite high in European cities/countries. For an effective grid load management a charging management of the bus fleet is essential; furthermore a system approach combining

[4] Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles, https://eur-lex.europa.eu/eli/dir/2019/1161/oj

[5] European Commission, 2019: Clean transport, Urban transport -

Clean Vehicles Directive, https://ec.europa.eu/transport/themes/urban/clean-vehicles-directive_en bus operation and charging strategies is necessary – bus and charging infrastructure has to be optimally linked.

Aspect	Opportunity charging (OC)	Depot charging (DC)	Remarks
Charging technology			
In depot	o	o	Both system topologies can utilize same depot charging solutions
On route	+	-	OC systems utilize automated connection devices, while DC systems typically have manual connection interface
Power grid connection	o	-	OC: 350 – 500 kW each charger; DC: 10 – 15 MW (100 – 200 buses) each charger 30 – 50 kW
Personnel demand	o	o	-
Investment cost Small fleet Big fleet	 - +	 + -	Low TCO is possible (scalability) - DC with low/mid utilization - OC with high utilization
Operation			
Line management	o	+	OC more sensitive to charging system disruptions but higher battery capacity solves that DC has smaller but more reliable operational range requiring adaptation in operation schedule.
Turn times	o	+	OC charging time at turn
Circulation	+	-	-
Personnel demand	o	-	More drivers for more buses of DC
Rail replacement traffic	+	-	-
Vehicle			
Number of buses	+	-	More buses needed for DC
Zero emissions	+	o	Often fuel heating for DC and OC in some Northern countries
Technology	o	o	-
Personnel qualification	o	o	-

„+“ solved
„-“ challenging
„o“ neutral

Figure 1: Assessment of charging technologies

Fleet management

One very important aspect for the further future development of battery bus systems is an advanced fleet management. Fleet management can be utilised to optimise the operation of electric bus systems. Especially when high scale OC bus systems are considered, fleet management has functions to ensure optimal charging operations. For example, system reliability can be potentially improved by charging priorisation, which ensures the buses should always have sufficient charge before departure. Moreover, the utilisation of the existing infrastructure and electric bus component (battery) aging can also be improved by smart charging applications that avoid unnecessary high charging powers. For instance, if a bus has relatively high state of charge and long turnaround time, lower charging power may be used to decrease the charging stress on battery and even out power demand from the grid. In addition, fleet management could also perform active monitoring on certain indicators on the fleet. For example, tracking component state of health, suggest more optimal duty cycle circulation to even out the wear of the fleet. Fleet management applications are still mostly in the development phase at this time.

Performance indicators

The key performance indicators for battery electric bus systems are

- Operating costs and energy consumption
  - Energy costs for driving (€/km): including electricity (from grid) and heater fuel
  - Operational driving distance (%/km): operational (on route) distance driven compared to the planned bus circulation
  - Total electricity consumption (kWh/km): total charged external energy (from charger) / kilometres driven (both on route and total km’s)
- Charging system performance
  - Time required positioning the bus at the charger (s): time to manoeuvre the bus to the charger. From arrival at the charger proximity to the point when the driver initiates the charging.
  - Total charging time (s): charging duration per sequence step from the charging start command to bus being ready to leave.
  - Charging node utilization (%): time when the charging position is occupied / time available. Time occupied includes the active and dead times.
- System performance
  - Depart on schedule (%): percentage of departures left on schedule
  - Availability of the vehicles (%): percentage of the time that the vehicles have been available for service
  - Availability of the infrastructure (%): percentage of time when charging service is available / calendar time

As additional indicators the following are relevant:

- Powertrain electricity consumption (kWh/km): inverter consumed electricity/kilometres driven (on route)
- Heating electricity consumption (kWh/km): electricity consumed by the HVAC system (both on route and total)

- Auxiliaries electricity consumption (kWh/km): electricity consumed by other electric auxiliaries, such as power steering, air compressor and DC/DC (on route)
- Fuel consumption (l/h): fuel heater fuel consumption vs. temperature
- Charging efficiency (%): electricity from the grid/electricity into the battery
- Dead time in charging (%): Dead time in charging/total charging time
- Battery efficiency (%): electricity out from the battery/electricity into the battery
- Total system energy efficiency (%): electricity out from the battery/electricity from the grid
- Minimum SoC in operation: lowest battery state of charge in operation
- Average delta SoC in operation: estimate from operational data
- Battery health, SOH (%): Percentage of the remaining battery capacity versus battery nominal capacity

Other low- or zero-emission bus systems

Beside battery electric buses also hydrogen fuel cell buses, and synthetic biofuels and E-fuels (made from CO_2 and electricity) with an internal combustion engine (ICE) are future options for low- or zero-emissions bus systems. The application of biomethane and hydrotreated vegetable oil (HVO) is an option; in future the application of synthetic biofuels is also possible. Battery electric buses have a limited range by one charging, and can be applied in urban areas. If there is the need for longer range buses hydrogen fuel cell buses and biofuel ICE buses might be a suitable alternative. In many countries hydrogen strategies are available, but the provision of green hydrogen is still very challenging. However, just as with the battery electric buses, further technical developments and significantly lower procurement costs for H_2 vehicles or tax incentives for the use of renewable fuels are needed here.

Below Figure 2 shows a qualitative assessment based on expert judgements on the different bus technology systems compared to diesel covering the aspects of fuel/energy supply – charging/fueling system and bus technology. Currently there is no “one fits all bus technology”, but battery electric buses have strong advantages in terms of technology and short term introduction.

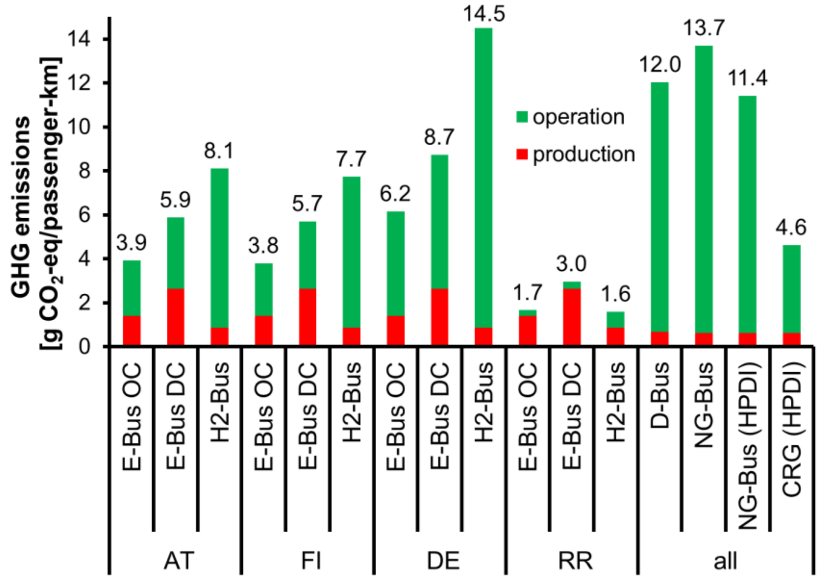
Aspect	Battery electric bus	Hydrogen fuel cell bus	Synthetic biofuel ICE bus	E-fuel ICE bus	Diesel ICE bus
Fuel/energy supply					
State of technology	+	o	-	-	+
Renewable energy	+	o	o	-	-
Efficiency (WtT)	+	o	o	-	o
Investment costs	o	o	-	-	+
Integration in existing infrastructure	+	o	o	-	+
Charging/fueling system					
Integration in existing infrastructure	o	o	+	+	+
Driving distance per charging/fuel	-	o	+	+	+
Investment costs	o	-	+	+	+
Bus technology					
State of technology	+	o	+	+	+
Market availability	+	-	+	+	+
Efficiency (TtW)	+	o	-	-	-
Local emissions	+	+	-	-	-
Heating	o	+	+	+	+
Cooling	o	+	+	+	+
Investment costs	o	-	+	+	+
Operational costs	+	-	-	-	o

„+“ solved
„-“ challenging
„o“ neutral

Figure 2: Assessment of different bus system technologies

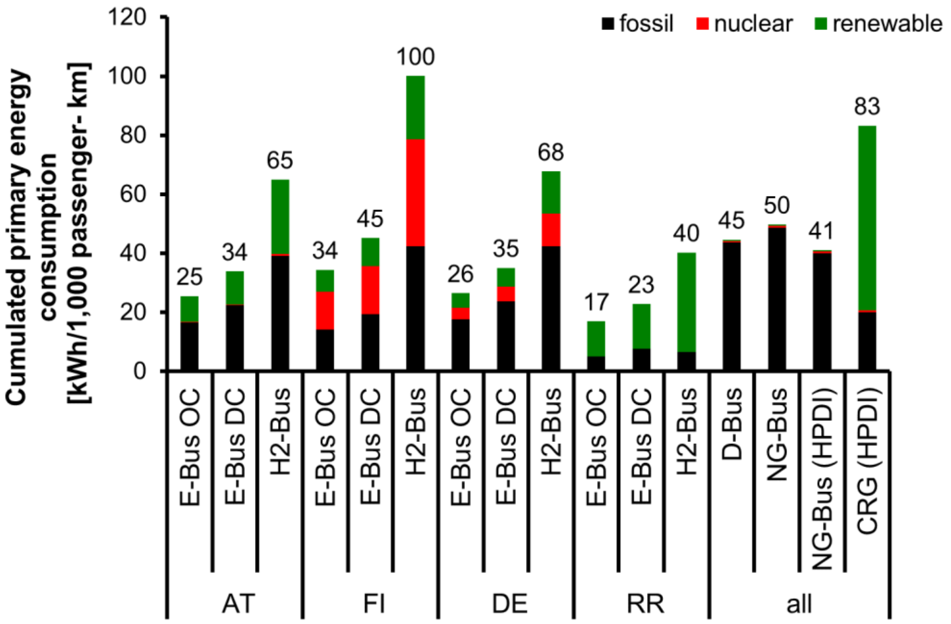
Environmental aspects

The environmental aspects of battery electric buses can only be assessed on the basis of Life Cycle Assessment (LCA) taking the entire life cycle into account – production of the bus (incl. battery) and the infrastructure, operation of the bus including the supply of the electricity and the end of life management of the facilities, e.g. recycling, reuse. The environmental effects deriving from LCA must be compared to a diesel bus (and hydrogen fuel cell bus if of interest). The environmental benefits of battery electric buses can be maximized if additional renewable electricity is used and future battery production will be on high production capacity realising economy of scale efficiency potentials and using renewable energy. The current battery production mainly in Asia is associated with relevant GHG emissions and fossil energy demand in the LCA of current bus systems. By using a high share of renewable electricity for battery electric buses, the total GHG emissions (Figure 3) and fossil energy demand (Figure 4) are lower than for diesel buses, and hydrogen buses. Battery electric buses have no local emission (e.g. PM, NOx) and contribute to the improvement of air quality in cities.



OC….opportunity charging; DC….depot charging overnight;
RR…."Renewable Republic": fictive country with 100% renewable electricity; D…Diesel; NG….Natural Gas;
HPDI….high pressure direct injection; CRG….Compressed renewable gas (biomethane: 40% residues and 60% maize)

Figure 3: GHG emissions: LCA based comparison per passenger capacity kilometre



OC….opportunity charging; DC….depot charging overnight;
RR…."Renewable Republic": fictive country with 100% renewable electricity; D…Diesel; NG….Natural Gas;
HPDI….high pressure direct injection; CRG….Compressed renewable gas (biomethane: 40% residues and 60% maize)

Figure 4: Primary energy consumption: LCA based comparison per passenger capacity kilometre

Current trends

Focusing on current trends it can be observed that the battery capacity of both OC and DC buses is continuously increasing (Figure 5). Over the last 2 years, the increase is especially big in OC buses that increased from ~60 kWh up to +200 kWh. E.g. in the Nordics, 12 m OC buses with battery capacity of over 200 kWh have already entered the service. The manufacturers are forecasting further increases in battery performance. In urban use, battery electric buses with ranges of 150 to 250 km can already be used on around one third of regular routes. The next generation is expected in 2021, and could then cover more than 300 km at a stretch. Regarding DC buses, high-capacity solid-state batteries are entering the markets. For example, Mercedes Benz has started offering bus models with up to 44 kWh solid-state battery from 2020.

Different sizes on battery electric buses are available, 12, 15 and 18 m buses. All major bus producers in Europe and in China are also producing battery electric 12 and 18 m buses, but also newcomers can be found on the market. Chinese manufactured buses are expected to enter the European markets. Currently, Chinese buses are not allowed to be sold to US, and since China has reduced the domestic incentives for battery electric buses, and as European countries have big pressure to decrease public transport related emissions, it is expected that the market amount of Chinese buses in EU will probably increase significantly. The European manufacturers have to significantly increase their production capacity, to meet the expected strongly increasing market demand. Many European bus manufacturers invest or start to invest now in new production facilities, e.g. VDL. The Chinese buses have traditionally been DC buses, however, the new generation Chinese buses (esp. made by BYD) can also be OC buses with small/medium size battery.

For the design of new light weight battery electric buses, more aluminium and plastic components are developed and integrated in innovative new use concepts.
A massive rolling out phase has started, as projects are realised by rolling out 100 battery electric buses at once. Examples are:

- Helsinki aims for 30% of city buses electrified by 2025 (equals to about 400 battery electric buses),
- cities of Athens, Paris and Madrid, and country of Norway, plan to remove diesel vehicles by 2025,
- other cities and regions have announced plans to stop purchasing conventionally fuelled buses, including Copenhagen (in place since 2014), London (announced for 2020), Berlin (announced for 2020) or Oslo (announced for 2020),
- UITP (Union Internationale des Transports Publics) has stated that more than 13 public transport operators and authorities in further 18 European cities have a strategy up to 2025; by then, they are expected to have more than 6,100 battery electric buses in service, representing 43% of their total fleet of 14,000, and
- according to one source, the amount of battery electric buses in Western Europe (+Poland) jumped to 1,687 in 2019[6] (from 548 in 2018).

Following main challenges are linked to the massive rolling out phase:

[6] Sustainable bus, 2019: Record year 2019. The big leap forward of e-bus market in Western Europe, link: http://www.sustainable-bus.com/news/record-year-2019-the-big-leap-forward-of-e-bus-market-in-western-europe/

- availability of battery electric buses and charges in daily operation (as less/no diesel buses are there for backup),
- integration of fleet management,
- energy and charging management to reduce cost and power capacity, and
- grid stability and quality.

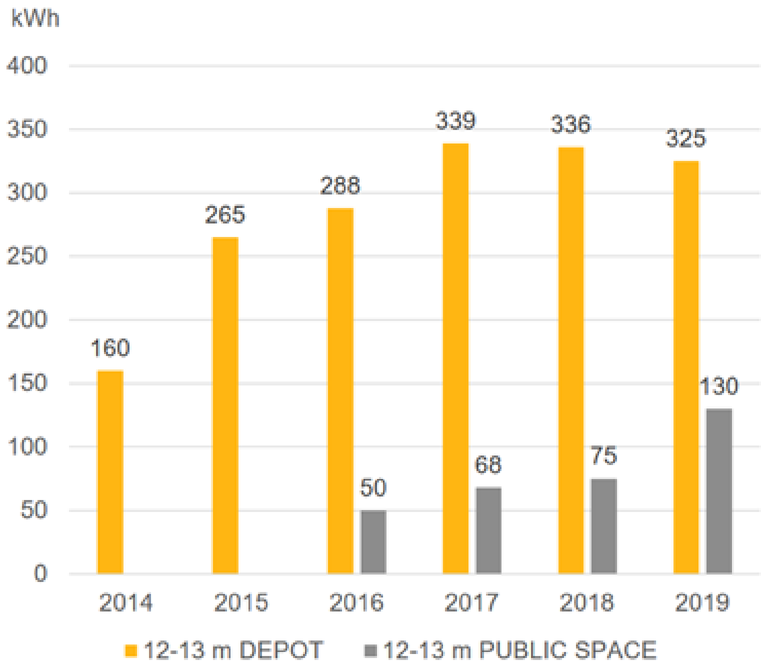


Figure 5: Average battery capacity, 12 – 13 m electric bus[7]

R&D issues

Focusing on the further development of battery electric buses, R&D needs are identified in the following fields:

- heating and cooling systems and strategies,
- inductive charging at stations/road,
- high power charging 1 MW and higher,
- light weight vehicles, e.g. plastic and aluminium,
- additional capacities to batteries for very quick charging,
- bus to grid (B2G) concepts, applications and business models, and
- integration of 2nd life batteries in depot charging system for peak shaving and additional renewable electricity storage.

In overall this summarized to the main future challenge to develop advanced fleet management systems with for battery electric buses for optimal daily fleet operation.

[7] Danchell, Joachim, 2019: An overview of zero emission buses in the Nordic countries – by the end of 2019, link: https://zero.no/wp-content/uploads/2019/09/03.1-Overview-of-zero-emission-bus-in-the-nordic-Joachim-Danchell-Movia.pdf

PROGRAMM

Wednesday, November 20, 2019

BEB SITE VISIT Amsterdam

Visit and test ride of battery electric buses and charging systems at Amsterdam Airport
9:30 **Welcome** at Schipol airport
9:30 – 12:00 **Testing and visit** of Battery Electric Buses at Amsterdam Airport
Experiences of Battery Electric Buses at Schipol, (Bart Kraaijvanger, connexion, NL)

EXPERT WORKSHOP

Welcome adresses
IEA HEV (Gerfried Jungmeier)
IEA AMF (Marcela Castillo Reyes)
proEME (Deniz Oezcan)
Aims of the Workshop (Gerfried Jungmeier, JOANNEUM RESEARCH, AT)

Session I: Practical Experiences and Technologies 15:00 – 18:00

Pan-Canadian Electric Bus Demonstration, (Charles Crispim, Natural Resources Canada, CA)
Current and Future Challenges of Battery Electric Buses in China (Jia Guorui and colleagues, CATARC, CN)
Overall Bus&Charging Technologies&System (Joel Anttila, VTT)
Discussion and main conclusions (all)

DINNER

Thursday, November 21, 2019

Session II: Economy and Markets 8:30 – 10:30

Economic Aspects & TCO of Battery Electric Buses (Joel Anttila, VTT, FI)
Battery Electric Buses Participation in Electricity Markets and Power Systems (Mattia Barbero, IREC)
Discussion and main conclusions (all)

BREAK

Session III: Advanced Charging and Environmental Aspects 11:00 – 13:00

Wireless Charging for Battery Electric Buses, (Theo Dusseldorp, consultant, NL)
Critical Raw Materials for Electric Vehicles, (Martin Beermann, JOANNEUM RESEARCH, Austria)
Environmental Aspects of Battery Electric Buses (Gerfried Jungmeier, JOANNEUM RESEARCH, Austria)
Discussion and main conclusions (all)
Summary of future perspectives for BEB and next steps (Gerfried Jungmeier, JOANNEUM RESEARCH, AT)

LUNCH

Session III: Case of Eindhoven 14:30 – 15:30

Experiences of Battery Electric Buses in Eindhoven, (Frank Bleijlevens, VDL Bus & Coach, NL)

BEB SITE VISIT Eindhoven

15:30 – 17:30 **SITE VISIT BEB in Eindhoven**
Visit and test ride of battery electric buses and charging systems in Eindhoven

PRESENTATIONS

Pan-Canadian Electric Bus Demonstration, (Charles Crispim, Natural Resources Canada, CA)

Main discussed issues

- 100% ZE vehicles until 2040 in CA (all vehicles classes)
- High share of renewable electricity (export excess to US)
- Raw material mining for batteries
- Pan-Canadian e-bus demonstration – route 26, Ontario
- Cutric – non-profit organization (research and innovation consortium: academia, government, industry)
- Phase I: Vancouver (1 route), York (2 routes), Brampton (2 routes)
- Overhead opportunity charging, 7 Siemens and ABB chargers (450 kW)
- 12 Flyer Buses (200 kWh), 6 Nova buses (76 kWh)
- Different charger operators in the 3 cities: utility, OEM (Siemens, ABB), transit agency: this is because e.g. in one city 6 different electricity distribution companies have different technical rules, very different regulative settings in the provinces of Canada
- Demo modelling (bus loggers, charger loggers, OEM data) for proper battery sizing, optimised infrastructure development, demand forecasting
- Montreal: 3 buses, 2 high power chargers: 1,1 kWh/km average (excl. waiting times); 35% recuperated braking energy
- Power demands for charging much lower than expected (real 100 kW per bus)
- Challenges: economics unique to site & application; bus net lifecycle savings was positive over 12 years, but charging infrastructure costs add differently; funding for bus investment is included in cost calculation;
- Inverted pantograph used – weather related decision for heavy snow conditions
- Trolley bus no future option in CA
- Roof mounted pantograph more weight (150 kg) on the bus, inverted needs communication with bus. In Norway both solutions are operated
- Range limitation in very cold climates changes operation? Norway: additional biodiesel heater, also depot heating; driving energy difference winter-summer not more than 20%. Especially with depot charging and larger range, an external heater is required; with opportunity charging also electrical heating can be a solution.

Current and Future Challenges of Battery Electric Buses in China (Jia Guorui and colleagues, CATARC, CN)

Main discussed issues

- BYD has buses for depot and articulated opp charging, Ytong depot buses
- 2018: only 15% new diesel buses, 85% batt buses
- List of cities in China with batt buses!
- Mainly depot charging, mainly 8-9m and 10-11m buses, big batteries (~200 kWh), average range 380 km?
- Big buses >12m opp charging at final stations ("double pistols")
- 2018: 140 Wh/kg energy density for pack+cooling
- On slide 12 you show the e-range and on slide 13 the battery capacity: we do not understand if these two figures suit together, as the battery capacity seems too low for the presented e-range – if no opportunity charging is applied? Or is bus going back to depot to be recharged during operation time? E-range in slide 12 is tested under the driving cycle by keeping the vehicle running at a constant 40km/h speed (according to standard GBT 18386-2017). At present, the electricity consumption of a battery electric bus is about 3.9-4.4kWh / (100km·t) under C-WTVC test cycle. Taking a typical 12m long battery electric bus as an example, which total weight is around 18t, the electricity consumption per 100km is about 70-80kWh. It can travel about 260-300km on a single charge (208kWh,weighted by production).
- What is the current electricity production mix used in the e-buses? What is the possible future development? And do you have information on the GHG and other emission from the electricity generation in China? According to the Statistical Bulletin on National Economic and Social Development in 2018 of the National Bureau of Statistics of China, thermal power accounted for 71% of the electricity generation in 2018 (thermal power consist of electricity generated by coal burning, fuel oil, gas, waste heat, waste pressure, waste gas, waste incineration, biomass), hydropower accounted for 17%, nuclear power accounted for 4%, and others accounted for 7% (Source: http://www.stats.gov.cn/tjsj/zxfb/201902/t20190228_1651265.html). Chinese government plans to promote the proportion of electricity generated by non-fossil energy to 50% by 2030 in Energy production and consumption transition strategy (2016-2030) (Source: http://www.gov.cn/xinwen/2017-04/25/content_5230568.htm). Followings are the emission factors for the upstream stage of the fuel cycle in 2015. (Sources: Evaluation Report on Greenhouse Gas and Air Pollutant Emissions of Automobile Fuel-Life Cycle 2018, http://www.sae-china.org/news/society/201809/2501.html)
    - GHGs: 855gCO2e/kWh
    - VOCs: 0.075g/kW
    - NOx: 0.671g/kW
    - PM2.5: 0.082g/kW
    - SO2: 0.433g/kWh
- What about hydrogen fuel cell buses? Are there any in operation in China? And what is their possible future perspective? Due to the high cost and insufficient technical maturity of fuel cell buses currently, fuel cell buses have been promoted less in the early stage. In 2016, 2017 and 2018, sales of fuel cell buses were 29, 116, and 395 respectively. China plans to promote fuel cell vehicles step by step in Technology Roadmap for Energy Saving and New Energy Vehicles (Source: http://www.sae-

china.org/news/society/201612/1200.html). Small-scale demonstration applications in the field of public service vehicles in specific regions will be developed in short term. By 2025, large-scale applications will be realized in the fields of urban private vehicles and public service vehicles.

Overall Bus&Charging Technologies&System (Joel Anttila, VTT)
Discussion and main conclusions (all)
Main discussed issues

- ZeEUS report #2 (2014-2018)
- ZeEUS 5 main challenges for e-bus deployment
    - High upfront costs
    - New operations
    - New ways to procure
    - Standards, interoperability
    - Reinforcing cooperation energy/bus
- From vehicle procurement to system procurement, requires early stakeholder involvement in the planning, require IT supported flee monitoring to optimise operation, local LCC models,
- Fast charging stations require a lot of space, conflict with inner city constraints of space and design; underground chargers 3-4 times more expensive (example Helsinki), potential of underground garage for space of infrastructure
- ASSURED EU project as follow-up of ZeEUS: next generation 600 kW charging solutions, interoperability solutions also with other vehicles (trucks etc.), wireless charging (100 kW)
- Roof mounted pantograph (schunk) already up to 1000 kW?
- Close to 1000 e buses in Europe (6% PHEV, 24% trolley hybrid), 50:50 depot and opp charging
- Nordics: 12-13m depot chargers: 320-340 kWh, opp charging: 70-130 kWh;
- 50% of ebuses are BYD and Ytong, rest mainly Volvo
- Cost diff Chinese-European buses: 50%
- Charging system providers: heliox, ABB, Siemens; 300-450 kW
- Finland: 20% of new buses between 2021-2025 must be e-buses (EU clean vehicles directive with country specific targets)
- Forecast EU: 2020 19% of new buses electric, 35% 2025, 52% in 2030
- Global stock 460.000 in 2018
- Germany funding 80% of additional upfront costs
- Torque reduction in Eindhoven ebuses due to increased abrasion of tires

Economic Aspects & TCO of Battery Electric Buses (Joel Anttila, VTT, FI)
Main discussed issues

- EAC Equivalent Annual Cost Vehicle+Charge+Energy+S&M+Urea (gasoline, Diesel)
- No general answer due to multiple influences to be addressed in TCO
- Line characteristics, bus operation concept, charging system, vehicle specifications
- LFP batteries mainly in China ebuses, LTO mainly in EU buses (LTO smaller energy density, but higher power)
- Delta SOC is smaller for oppcharging (0.3), higher for depot charging (0.8 – 0.9)---- affecting battery cycle life. LTO batteries have higher cycle life than LFP
- Cost analysis case Espoo line 11 (2014): 2 chargers 300 kW, 2-3 min stop, roundtrip 22km x 10 trips; see slides; type 1: large batt+depot, type 2 small batt+opp
- Charging efficiency 80-90%, depends very much on usage during the day for cooling/heating /fans running the entire day?
- Effecitve eff includes charger
- LTO has lower TCO than LFP in €/km (0.8 €/km vs 1.1 €/km) energy prices include taxes
- Additional buses for opp charging buses can be a topic due to time lost during the tour and missing for charging, in this case not required
- Sensitivity analysis increasing mileage per day: conventional buses: lower capex, higher opex, e-buses: higher capex, lower opex; but to consider: higher mileage per day affects lifetime in years? Battery usually have guarantees in years, bigger battery enables higher lifetime mileage
- Lifetime of buses: diesel – stricter emission limits, vibrations reason for exchange. E-bus: technology development is fast; trolley buses: more robust construction (produced by tram manufacturers)
- Costs of bus driver needs to be considered as well. In the medium term it should be 1:1 replacement of diesel bus; schedules of ebuses are adapted in a way that no additional ebuses (+drivers) are required for opp charging
- Sensitivity batter price LTO bus: has no big effect on TCO
- Cases Helsinki 2018 analysis: CEG cumulated elevation gaining
- NMC has lower charging power than LTO, but NMC has higher capacity and charging power in kW usually relates to capacity in kWh (the higher kWh, the higher possible kW)
- Has scale of economy a benefit, buying 100 buses at once for lower bus investment, and having synergies with several ebus lines served
- Challenge for tenders of PTAs, they don’t ask for number of buses, but quality of service, environmental and cost criteria. PTOs take high risks for bigger fleets investments

Battery Electric Buses Participation in Electricity Markets and Power Systems (Mattia Barbero, IREC)

Main discussed issues

- Electric buses and flexibility of electricity system
- Price based and availability based = incentive driven (max number of activations/day); power costs (kW availability) and energy costs (kWh consumed)
- Depot charge: immediate, continuous and off peak charge: lowest depot power has continuous charging
- Opp charging by far the most expensive way of charging
- Bus2Grid of ebuses e.g. for balancing wind power during the night; or transporting cheap electricity from cheap charging spot to high cost electricity area

Wireless Charging for Battery Electric Buses, (Theo Dusseldorp, consultant, NL)

Main discussed issues

- Static (depot), opp wireless, in motion/dynamic
- 2014-2019, Summer 2019 final report
- Follow-up tasks: in the road conductive, dynamic wireless, overhead catenary
- Also bidrectionally charging possible, “drive around to earn money”
- Hertogenbusch 4x20 kW, camera assisted alignment of bus
- Drop down system for secondary coil of bus;
- Challenges: moving bus during passengers entering the bus, lowering charging efficiency; now “kneeling bus” with no moving part of the secondary coil, but higher gap
- Snow, ice: no technical barrier for use of wireless; no heating
- Passengers can remain in the car during charging, magnetic impact level the same as inductive cooking (6 micro-tesla); but no animal shall be in between the coils
- Efficiency: 90-96%, real 85%
- 20 to 80 kEUR for 100 kW
- Currently standard development is essential, today the same technology supplier has to equip the charging site and the bus-coil
- Benefit for inner city stations with space and design constraints
- But current bus standards are based on overhead charging, wireless development lagging behind
- Already installed charging systems will last longer than buses, what is the chance for wireless to enter markets

Critical Raw Materials for Electric Vehicles, (Martin Beermann, JOANNEUM RESEARCH, Austria)

Main discussed issues

- Social impacts of interest, important to review available information for reliabiltiy

Environmental Aspects of Battery Electric Buses (Gerfried Jungmeier, JOANNEUM RESEARCH, Austria)

Main discussed issues

- Dynamic GHG emissions of electricity mix over bus lifetime
- Different mix for overnight depot charging and during the day opp charging
- Additional electricity demand is usually coming from peak power plants? Depends very much on country
- Helsinki wants to include LCA in tenders, don't know how.
- Differentiate LCA results with different battery production sites
- Update in task 33 beginning of 2020

Experiences of Battery Electric Buses in Eindhoven, (Frank Bleijlevens, VDL Bus & Coach, NL)

Main discussed issues

- VDL 17.000 employees, € 6 Billion turnover (since 1993 bus production)
- Also Mini and BMW X1
- VDL coach factory in Eindhoven, city buses in Belgium
- Family owned company
- Automated vehicles for container port Rotterdam, also parts for CERN
- E-buses: 80 projects, 500 vehicles in operation, 1000 buses sold
- Eindhoven since 5 years
- Takeaways:
    - Stakeholders need to be on board: PTO, PTA, grid company
    - Interoperability not given
    - Responsibilities and roles need to be defined
    - Project mgt essential: clients want one stop shop
    - System responsibility to be appointed
    - Value of training, drivers, workshop personnel, planning department
- Citea Electric: 5 days 2.340 km, 1,32 kWh/km, 73 % SOC average
- Next steps: bigger batteries, more flexibility for charging strategies, reducing charging stations along the lines, depend less on opp charging
- But: Grid limitations for connections higher than 2 MW in NL
- Depot charging: first phase 4,3 MW grid connection used, but already 10 MW installed for extension. Also a reason to switch more towards depot charging
- No wireless charging currently, expensive, efficiency
- Integrated system (bus, charging…) thinking was biggest challenge for VDL, working with new people (electric engineers…)
- Hydrogen FC buses wait to be licensed, range extender solution
- TCO: ebuses catch up with Diesel buses

Task 33 “Battery Electric Buses”

Members: Austria, Canada, Finland Germany, Spain, South Korea

The objective of the Task 33 (2016 – 2019) is to analyse and assess the current state of technology & demonstration experiences of battery electric buses. This covers on one hand the bus technology e.g. battery or capacitor system, and on the other hand the charging infrastructure, e.g. fast charging stations at the bus stop and its optimal integration in an urban infrastructure, e.g. synergies with trams, metro or trolley bus systems. The task work is done based on an analysis of ongoing demonstration projects of battery electric buses worldwide. Based on this the future perspectives and challenges for battery electric buses are analyses and described. This includes the identification of major challenges e.g. technology, costs, public acceptance and the necessary R&D demand. Finally, the key aspects for a successful broad introduction of battery electric buses and the necessary frame work conditions are concluded.

The work is done in a close cooperation of the relevant stakeholder from the three focus groups:

- Provider of public transportation services
- System and technology provider
- Research institutions

The results are continuously documented and disseminated via presentations, workshops, conference contributions and publications.

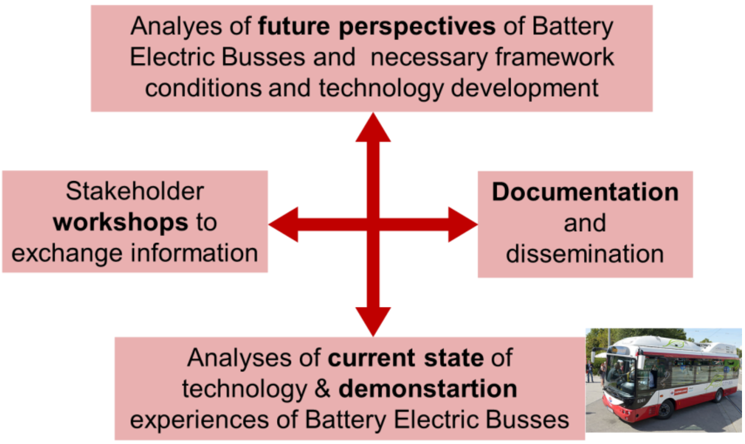


Figure 2: Objectives

The major activities are

- Identify &analyse state of technology and systems of battery electric buses
- Collect and document „International Success Stories“ in a common format
- Give overview of systems &technology providers with characteristic data
- Stakeholder involvement in 2 - 3 Workshops in combination with site visit
- Analyse combination of trolley and battery bus systems
- Integration and use of existing infrastructure of trams, trolleys and metro
- Identify success factors, e.g. size of bus, distances between bus stops
- Define loading strategies
- Analyse sustainability issues – economic, environmental &social aspects
- Identify R&D demand
- Conclude and summarize future perspectives
- Publish IEA HEV glossy Brochure of results
- Presentations and contribution at conferences

The most important activity of the working method is the organization of workshops in different member countries to involve the stakeholders in the value chain of battery electric buses, e.g. provider of public transportation services, system and technology provider, research institutions. The organization of workshops with participation from industry, research organizations, technology policy experts and governmental institutions provides an international basis for the exchange of information on the relevant activities. The focus of the expert workshops is to analyse, discuss and document the

1 State of technology for battery electric buses
2 Future perspectives of battery electric buses

The workshops are combined with a site visit to an ongoing demonstration of battery electric buses in daily life application.

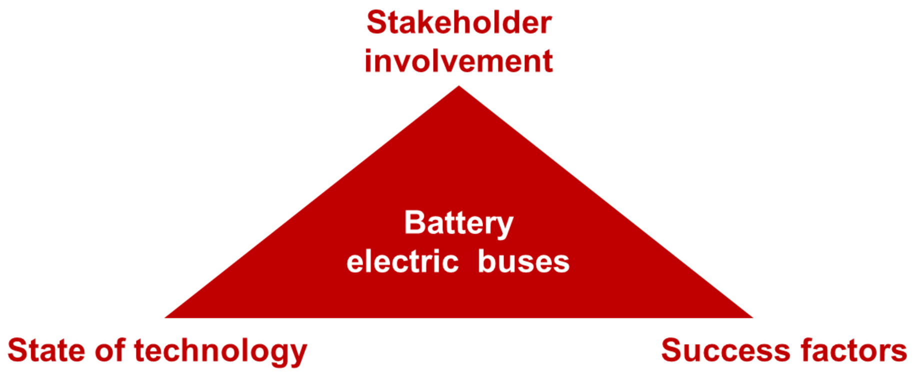


Figure 3: Working method

Operating Agents

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