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Analysis of an emission-free public transport (xEV)

Daniela Schneider[1], Laura Langenbucher[1], Lukasz Brodecki[2], Markus Blesl[2], Ralf Wörner[1]

[1]Institute of Sustainable Energy Engineering and Mobility, University of Applied Sciences Esslingen, Kanalstraße 33, 73728 Esslingen am Neckar, Germany, daniela.schneider@hs-esslingen.de

[2]Department of System-analytical methods and Heat Market, Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Heßbrühlstraße 49a, 70565 Stuttgart, Germany

Summary

In 2019 the Directive (EU) 2019/1161 set the course towards an emission-free public transport in Europe. In this regard, the purpose of the present paper is to provide recommendations for an economic operation of a local public transport with the analysis of different xEV drive types by means of Key Performance Indicators (KPIs). Subsequently, the previously identified KPIs of emission-free public transport in the area of Stuttgart will be evaluated. Due to the limited space in the inner city of Stuttgart, fuel cell electric vehicles can be seen as preferred choice.

Keywords: public transport, bus, ZEV (zero emission vehicle), mobility concepts, electric drive

1 Introduction

In addition to the energy transition in the areas of space heating and energy, the transport sector must be restructured in order to achieve the set mitigation goals of the European Union (EU) and Germany. The transport sector must also change with regard to the Directive (EU) 2019/1161, also called Clean Vehicle Directive (CVD). This directive stipulates that public purchasers and private companies operating public transport services must take into account energy consumption and environmental impacts when purchasing a vehicle. For this, it is necessary to consider the following aspects: energy consumption, carbon dioxide (CO_2) emissions, particulate matter emissions, non-methane hydrocarbon emissions and nitrogen oxide emissions [1].

The result of this study should help bus operators to increase their economic efficiency in zero-emission local public transport by choosing the right concept. The aim is to show the properties of different drive technologies with regard to the identified KPIs.

2 Results of the Local Public Transport System

The TIMES Local Stuttgart Model

The basis of the approach is the model TIMES Local, derived from the TIMES model generator [2]. An energy system is mapped in bottom-up technological detail as a network of processes (e.g. power plant types, transport technologies), goods (energy sources, materials) and the resulting emissions in the form of a reference energy system aggregated in one node. In the linear optimization model, the system base, future demand in the individual sectors and primary energy source prices as well as the parameters characterizing the technologies and energy sources are specified. The objective of the model is an integral expansion and deployment planning of the energy system under the premise of cost minimization. TIMES Local is an application which focuses on considering those processes relevant for a city or a district, thus in this study an analysis was conducted for the city of Stuttgart including the sectors of public electricity and heat supply, private households, trade, commerce, services, transportation, industry and the imports of energy sources [2]. As part of the optimization, an integral expansion and deployment optimization are carried out over the entire modeling period in perfect foresight. The modelling horizon consists of 5-year steps from the year 2010 to 2050. The time resolution is divided into five type weeks with hourly time increments. Four type weeks each correspond to a season (672 time increments per year), and the fifth characterizes a peak week with an hourly resolution (an additional 168 time increments per year) to illustrate a high feed-in of fluctuating renewable energies. Reference year for weather data and generation profiles is the year 2011. Detailed information regarding the model can be found in [3]. The focus of this scenario analysis is the evaluation of the decarbonization pathways within the public transport sector as well as its impact on the achievement of local greenhouse gas emission reduction targets.

With the TIMES Local Stuttgart Model, three scenarios of the expansion of emission-free public transport are considered [2–4]. The analysis is based on a reference scenario, named KLIM containing the goal of reducing greenhouse gas emissions by 95% by 2050 compared to 1990 according to the master plan of the city of Stuttgart [5]. According to the planning of the city of Stuttgart, the “KLIM+” scenario contains additionally to the greenhouse gas reduction target a decreasing demand for mobility demand in motorized private transport, which in the model is defined as an exogenous modal shift in transport services to public and rail transport. At the same time, there is a partial shift of freight traffic from truck transport to rail freight transport implemented in the scenario. The use of biofuels will be abandoned from 2040 onwards due to the environmental impacts of these fuels. The growth in electric vehicles is predetermined until 2030 and is documented in Tab. 1. The restrictions and specifications of the CVD for the public transport sector have not been implemented in this scenario analysis. Emission reduction goals in the transport sector are considered indirectly through increased electrification. Explicit targets for the expected penetration of electric mobility are set for the year 2030 - in the years to come, however, the further course of development will be a model endogenous decision. The third scenario named "KLIM+LOW" contains identical general conditions to "KLIM+", but a significantly delayed and slowed development of electromobility until 2030 is assumed and investigated [6–8].

Table1: Scenario definition regarding market penetration of xEV based on [6]

2030		BEV	PHEV	xEV-Share
No xEV share (KLIM)	Cars	-	-	-
	Light duty	-	-	-
	Buses	-	-	-
xEV high (KLIM+)	Cars	16.47%	10.60%	27.07%
	Light duty	11.62%	n.a.	11.62%
	Buses	21.02%	n.a.	21.02%
xEV low (KLIM+LOW)	Cars	3.33%	6.67%	10.00%
	Light duty	4.00%	n.a.	4.00%
	Buses	7.00%	n.a.	7.00%

Fig. 1 shows the results for the final energy consumption within the transport sector for the timeline between 2015 and 2050. Between the scenarios no drastic differences can be identified. The final energy consumption within the transport sector decreases from around 12,000 TJ per year in 2020 to a level below 6,000 TJ in 2050. The causes of this reduction are efficiency increases in fossil-fuelled cars as well as a step-wise electrification of the transport sector. The initial technology distribution based on diesel and gasoline is gradually replaced after 2025. The resulting decline in energy consumption levels can be mainly attributed to the high efficiency of energy conversion processes in electric vehicles compared to conventional combustion engines. Furthermore the share of biofuels and hydrogen increases compared to the initial state in all scenarios.

By taking a closer look at the developments between the scenarios, comparable conditions can be observed for the years 2020 and 2050. In the intermediate periods however, differences in the final energy consumptions between the scenarios occur. A higher final energy consumption can be reliably located in the KLIM+LOW scenario. In this case the lower penetration rate of electric vehicles leads in comparison to the KLIM+ scenario to an overall higher final energy consumption. Furthermore, the exogenously given higher demand for mobility in the KLIM case requires more restrictive measures for a decarbonization of the transport sector. This means that even if it is proving challenging to shift the modal split from motorized private transport to public transport, electromobility could be an effective means of reducing energy consumption.

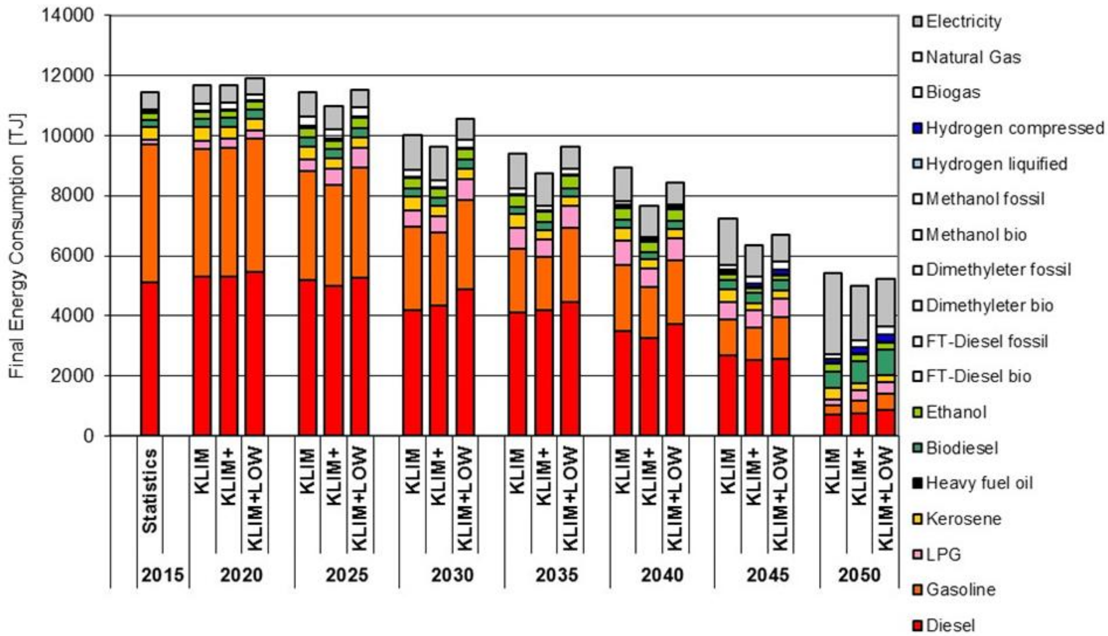

Figure1: Scenario comparison for the final energy consumption within the overall transport sector

Consider now the initial state of the final energy consumption of the buses active in Stuttgart for the year 2020 (Fig. 2). Here we observe that, on the basis of today's stock, the majority of buses are still powered by conventional fuels (diesel, natural gas) or, to a lesser extent, blended biofuels. For the year 2050, however, we see a drastic shift to alternative fuels in all of the scenarios. We can observe, that until 2050 the two groups of hydrogen and electricity as energy carriers supply fully the public transport sector. Both energy sources are used in TIMES Local, as buses tend to use hydrogen on longer routes and intercity buses, while electrification predominates on shorter inner-city routes. The KLIM+LOW scenario differs only slightly from this. Due to the fact that the use of electric mobility and the associated infrastructure development are delayed, we see a slightly higher proportion of hydrogen powered vehicles at the expense of electric buses.

In addition an earlier decarbonization transition with alternative fuels can be observed in KLIM, as seen by the year 2040. This is due to overall higher emission levels in KLIM in the total transport sector, driven by exogenously higher demand motorized individual transport, which has in relation to public transport typically a higher emission footprint per passenger-kilometer.

The overall local production of hydrogen in 2050 sums up to 72 TJ in the KLIM scenario for the city of Stuttgart compared to 185 TJ in KLIM+ and 218 TJ in KLIM+LOW, representing only 1.9% of the overall final energy demand in the transport sector (KLIM), 4.2% in KLIM+ and 4.7% in KLIM+LOW. Nevertheless, in all scenarios hydrogen plays a decisive role in an emission-free public transport, which is why in the following we conduct a detailed cost analysis of a hydrogen supply infrastructure for the Stuttgart metropolitan area.

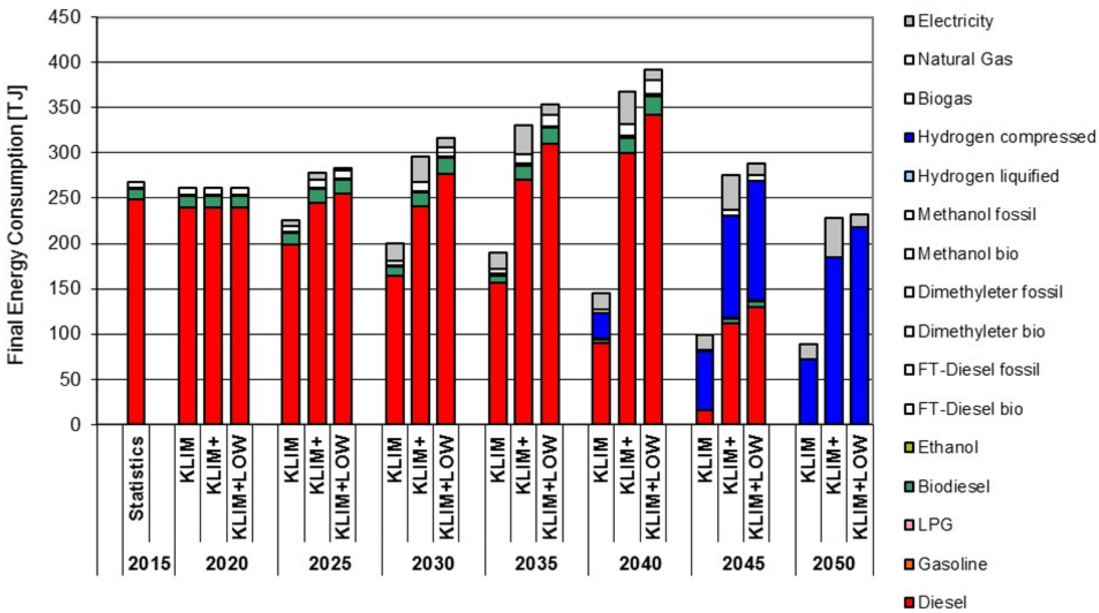

Figure2: Scenario comparison for the final energy consumption within the bus public transport sector

Public transport provided by buses represents only a small share of the total energy consumption in the transport sector, as the overall composition clearly reflects. In 2015 the emissions of busses account for 0.5 % of the total CO2 emissions within the transport sector in the city of Stuttgart, compared to 66% within the motorized individual transport. Here the motorized private and truck transport play a dominant role in the distribution of energy consumption in the transport sector. Nevertheless the complete transformation pathway of the public transport sector to electricity-based and carbon neutral technologies underline the necessity of implementation of measures to achieve overall emission reduction goals on a local level. Therefore, the public transport of buses can make a contribution to the reduction of the total emissions. In sum, the decarbonization of the transport sector represents a challenge for the transformation of the overall energy system.

3 Improvement of the Economic Efficiency for xEV in Public Transport

The Directive (EU) 2019/1161 forces European transport companies to turn to clean and zero-emission drive concepts [9]. Clean vehicles drive with alternative fuels. This includes electricity, hydrogen, specific biofuels, synthetic and paraffinic fuels, natural gas (including biomethane) and liquefied petroleum gas [10]. Zero-emission vehicles are clean vehicles that do not have an internal combustion engine or if they have one, emit less than 1 g CO_2/kWh [9]. In this paper only zero-emission drive technologies are examined. All drive types are compared with diesel buses.

These concepts involve fuel cell electric vehicles (FCEV), battery electric vehicles (BEV) as well as hybrid technologies (HEV) from these variants, such as a fuel cell range extender (FC-REX). Battery electric vehicles can be differentiated into vehicles with overnight charging (ON), opportunity charging (OC) and battery swapping (BS).

In this paper some important KPIs are identified, which can have an influence on the choice of a drive technology. The selected KPIs are summarized in Fig. 3 and described and evaluated below.

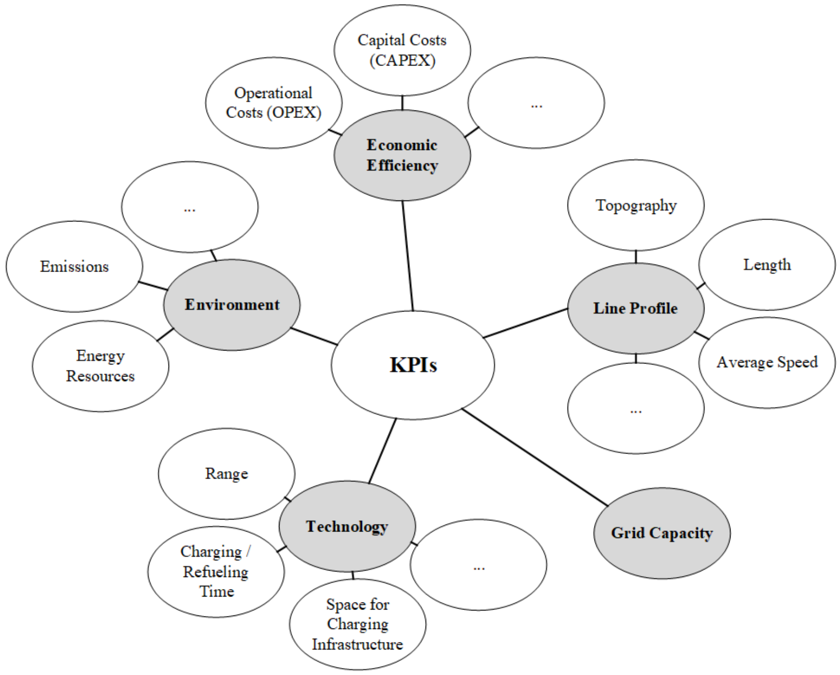

Figure3: Overview of the KPIs

3.1 Explanation of the KPIs

Line Profile

The line profile has a significant influence on the choice of a drive technology. The technology chosen must be able to ensure the smoothest possible operational sequence. Various factors affect the KPI "Line Profile". For example the topography and the average speed, which influence the driving cycle and thus the consumption, the length of the route and the duration of the journey. Therefore the consumption, the range, the charging or refueling time as well as the line flexibility are important influencing factors.

In this paper a distinction is made between two line profiles: intercity and inner-city. An inner city line is usually shorter than an intercity one. Due to many stops it can only reach a low average speed. This is not only due to the number of stops, but also to the maximum speed of 30 or 50 km/h in the city and the constant braking in front of stops, including traffic lights in urban areas. In the case of an intercity line, the bus covers longer ranges between the stops. As a result, it has fewer braking processes and therefore a higher average speed. Braking in front of traffic lights should also be found less frequently, since these are not as common on intercity routes. An express bus line is a mixture of the two line profiles presented. The buses run in urban areas, but have fewer stops and can therefore reach a higher average speed.

Technology

There are different emission-free drive technologies, which are briefly presented here. A general distinction is made between vehicles with a battery electric and a hydrogen drive. The drive technology of a bus influences, among other things, the following factors: the range, the charging or refueling time, the emissions, the investments in vehicle and the charging / refueling infrastructure and the reliability.

Battery electric vehicles can be differentiated according to their charging technologies. With overnight charging technology the vehicle is only loaded at the depot. Such breaks are usually found at night. Charging is often carried out using a plug (conductive) but inductive methods can also be used. Since only breaks can be used for charging the buses have range restrictions. Charging a vehicle during the stay at designated stops is called opportunity charging (OC). The range problem of an ON bus thus can be eliminated. Conductive (e.g.

pantographs) or inductive charging technologies are used for charging. Another method is to swap the battery (battery swapping (BS)). The empty battery is replaced by a charged one. The exchange can be done manually or automatically. The battery is changed within a short time, but the bus must first go to the swapping station. This concept leads to significant higher investments [11].

In a fuel cell bus, hydrogen is converted into electrical energy. This technology is most similar to diesel buses. The buses are refueled at centrally located hydrogen filling stations within a short time. The range requirements can be met [12].

Environment

The drive concepts mentioned above also differ in terms of their effects on the environment. Different types of emissions can be identified that can influence the choice of technology. Five types of emissions are considered in this paper: well-to-wheel emissions, carbon dioxide, nitrogen oxide, particulate matter and noise emissions. Tab. 2 shows the evaluation of the different drive concepts for the emissions described. This KPI has an impact on the choice of drive technology to the extent that diesel vehicles are subject to emission costs [13] and the Directive (EU) 2019/1161 stipulates minimum targets for the proportion of clean commercial vehicles from the beginning of August 2021 [9].

Economic Efficiency

Different KPIs affect the Total Cost of Ownership (TCO) analysis. This is part of the economic analysis and thus of the KPI “Economic Efficiency”. For the bus operator this KPI is one of the immediately relevant decision criteria because it reflects the expected cost per kilometer. A diesel vehicle today mostly performs better than an alternative drive vehicle in terms of this KPI. Hence, bus operators have to analyze whether it is worthwhile to switch the line or whether it generates losses. One way of limiting or eliminating is through funding, which is not considered in this paper, since it depends heavily on the funding country.

Grid Capacity

Grid capacity also has a significant impact on the technology to be selected. Regular operation depends on the buses driving. The technology cannot be used, if the power network in the depot or along the route is not stable enough to absorb the additional load by charging. If the power network has to be expanded, considerable costs can be expected. This KPI only affects buses that need to be powered along the route or in the depot.

Table2: Assessment of drive technologies [14, 15, with additions]

	Diesel (Euro VI)	Battery (ON)	Battery (OC)	Battery (BS)	Fuel cell
Range	++	-	-	+	0
Charging / Refueling Time	++	-	-	0	+
(Line)Flexibility	++	0	-	-	++
Well-to-Wheel Emissions	-	0	0	0	0
CO_2 Emissions	-	++	++	++	++
Nitrogen Oxide Emissions	-	++	++	++	++
Noise Emissions	-	++	++	++	++
Particulate Matter Emissions	-	++	++	++	++
Line Operation Costs	++	-	0	-	-
Vehicle Costs	++	-	-	-	-
Investment Infrastructure	++	-	-	-	0
Space for Charging Infrastructure	++	0	-	-	++
Needed Grid Capacity	++	0/-	0	-	++
Renewable Energy Resource	-	possible	possible	possible	possible

++: very good, +: good, 0: satisfying, -: bad

3.2 Case Study

In the further course of the paper a case study will be used for illustration. The graphics below refer to an express bus line in the region of Stuttgart. The line has a circumferential length of approximately 46 kilometers. The buses run every half hour on weekdays, with a compression to a 15-minute interval during rush hour from 6:00 a.m. to 8:00 a.m. and from 4:00 p.m. to 6:30 p.m. This means that the nine buses cover approximately 540,000 kilometers per year, which corresponds to approximately 60,000 kilometers per year per bus. The line runs through thinner and more densely populated areas.

A TCO analysis for four different technologies was calculated for the express bus line. The diesel serves as a comparison value. In addition to a pure hydrogen and a purely battery electric vehicle an FC-REX was considered that combines these two technologies. Within the example, the battery swapping and the overnight technology are not followed up. The battery swapping technology cannot be regarded as sustainable due to the increasingly necessary production of batteries. In addition there are increased costs for the replacement batteries as well as the establishment of a battery replacement point and personnel to monitor the swap. This is not an economical alternative for bus companies. Overnight technology is also excluded because the battery capacity for the route length is not sufficient to be able to use buses of this technology. Fig. 4 shows the results of the TCO analysis for the three drive technologies mentioned. The results of the diesel form the starting point. Costs for emission are included in OPEX.

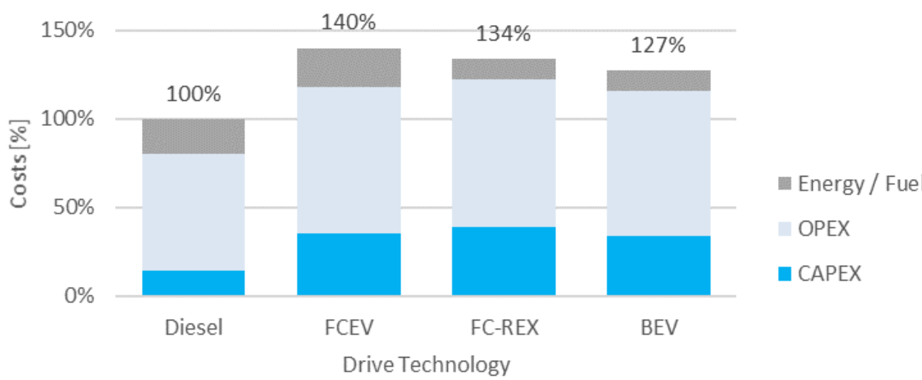

Figure4: TCO analysis of the express bus line (2020)

It can be seen that all three alternative drives are more expensive than the diesel. This is due, among other things, to the expensive acquisition costs for vehicles and the associated infrastructure. By an EU funding named JIVE, fuel cell buses can be bought in the European Union for a maximum price of 625,000 to 650,000 euros [16]. The values for the FCEV do not include any costs for setting up a hydrogen filling station, as this is not necessary at the depot. The charging infrastructure is included with FC-REX and BEV. A net price of 8 euros per kilogram was assumed for the hydrogen costs and 0.17 euros per kilowatt hour for the electricity price. The net diesel price was set at 1.14 euros per liter.

The KPIs are weighted by considering the influence of the respective KPI on the TCO analysis. For this purpose, starting from 100%, the indicator is increased or decreased by 50% in 10% steps and the impact on the TCO analysis is analyzed. Based on these results, the KPIs can be ranked for each technology. It is taken into account that changing one factor usually affects various other factors. A change in consumption affects fuel costs for example. The number of kilometers affects personnel, fuel and maintenance costs. The latter are also influenced by the charging infrastructure, which, like the buses, requires maintenance. The number of buses required has an impact on the amount of investment for the vehicles, maintenance costs, insurance costs and the costs for the required charging infrastructure. A change in the energy / fuel price (diesel, hydrogen, electricity) affects fuel / energy costs. The influences are summarized in Tab. 3.

Table3: KPI matrix

	Energy / Fuel Costs	Personnel Costs	Maintenance Costs	Vehicle Costs	Insurance Costs	Charging Infrastructure Costs
Mileage	x	x	x			
Number of Buses			x	x	x	x
Vehicle Costs					x	
Personnel Costs						
Maintenance Costs			x			
Consumption	x					
Energy / Fuel Price	x					
Charging Infrastructure Costs			x			

The influence of individual parameters on the TCO result can be seen in Fig. 5. The change in individual parameters has different effects on the result of the analysis depending on whether it is a diesel bus or one with an alternative drive. It can be clearly seen that Fig. 5a, for the diesel technology, differs from the others, while they are very similar.

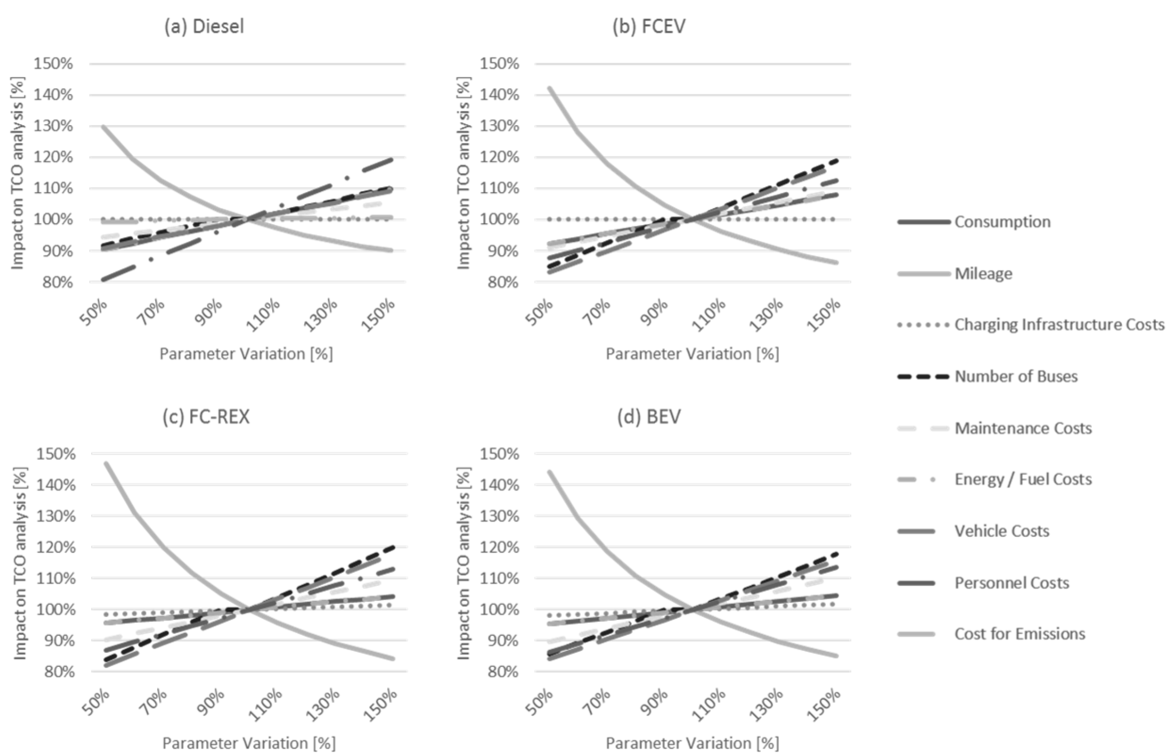

Figure5: Impact of the KPIs on the TCO analysis

Except for the number of kilometers, all other factors have a negative impact on the TCO analysis if they are increased. This is because a TCO analysis calculates the costs per kilometer: the more kilometers increase, the lower the costs. Increasing or decreasing the number of kilometers on a diesel vehicle has less of an impact than on a vehicle with an alternative drive. Personnel costs have the greatest negative impact on a diesel bus. Due to the high acquisition costs of alternative technologies, the number of vehicles has the highest negative effect on zero-emission vehicles.

As can be seen in the figure, the ranking of the KPIs varies. They can therefore be assigned a different importance depending on the drive technology. Due to lower acquisition costs, the number of buses and vehicle costs are less important for a diesel bus than for a battery electric, fuel cell or FC-REX bus. Instead, personnel costs play a more important role in diesel, as consumption and fuel price do. The emission costs, which are only incurred for diesel buses, have only a relatively minor impact on the TCO analysis (±1%).

Concluded, the following aspects are of primary interest in order to be able to guarantee a rough initial estimate of costs: number of buses, vehicle costs and mileage. The other factors may be taken into account for a closer look.

4 Discussion of an Emission-Free Public Transport in Stuttgart, Germany

As shown in chapter 2, the number of buses with alternative drives will increase significantly over the next 20 years. First, the number of hybrid buses will increase significantly. Battery electric buses will also appear in the depots, but not primarily. Depending on the scenario (KLIM, KLIM+, KLIM+LOW) hydrogen buses will increasingly be used from 2040. They will make up the majority of buses in all the three scenarios from 2045. However, this is the bus technology which is currently still around 40% more expensive than the diesel bus used previously. That this technology receives such a large influx can be explained by the falling costs for alternative drives in the next few years. Tab. 4 gives an overview of the expected cost degressions.

Table4: Expected cost degressions

		2020	2030	Source
Energy / Fuel Price [%]	Diesel	100	~128	[11]
	Hydrogen	100	~85	[**]
	Electricity	100	~92	[17]
Cost for Emissions [%]		100	~203	[11, 14, 18]
Maintenance Costs [%]	Diesel	100	~115	[11, **]
	Fuel Cell	100	~51	[**]
	Battery Electric	100	~51	[**]
Personnel Costs [%]		100	~125	[***]
Vehicle Costs [%]	Diesel	100	~116	[*]
	Fuel Cell	100	~67	[*]
	Battery Electric	100	~67	[*]
Charging Infrastructure Costs [%]	Battery Electric	100	~81	[*]

* Own Calculations based on [11]   ** Own Assumption   *** Own Calculations based on [19]

If the expected cost degressions over the next ten years are included in the TCO analysis, the figure is completely different from Fig. 4. The total costs of the diesel increase by 19.3%. The costs per kilometer for a FCEV decrease by 17.4%, for a FC-REX by 17.5% and for a BEV by 16.2% compared to 2020. The results are shown in Fig. 6.

The results from chapter 2 initially assume an increase in hybrid vehicles, mostly diesel hybrid vehicles in stock. Vehicles with conventional drives will account for around 50% by 2040. The mandatory EU directive is not included in the forecast. However, it shows that the change to alternative drive concepts would also take place without them over time.

Therefore, the directive was criticized in a position paper by the Association of German Transport Companies (VDV). The association states that change is already planned in the long-term strategies of transport companies, which supports the forecast and can be seen in Fig. 2. Due to the quick introduction, which now is necessary due to the directive, buses have to be procured that currently do not have the necessary level of maturity and thus the reliability that is required. This would also make the transport offer less reliable. The VDV also points out that the charging infrastructure is still missing. The infrastructure would have to be set up before bus procurement and would take at least five years [20].

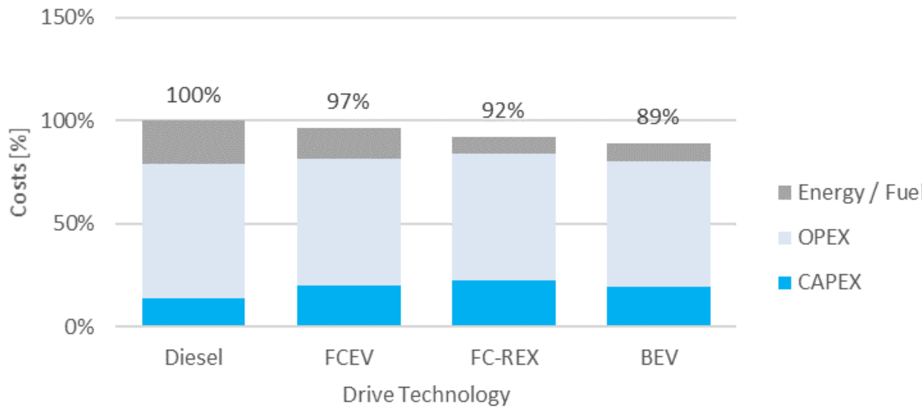

Figure6: Forecasted TCO analysis of the express bus line (2030)

The predicted TCO results (Fig. 6) for 2030 show that the costs for alternative drives will decrease in the coming years. However, the directive will apply from next year, so that the procurement of vehicles and the associated infrastructure will be necessary at this point. This places a heavy financial burden on companies, so they cannot experiment with technology, but have to commit themselves at the beginning.

5 Conclusion

To conclude, the demand for mobility services in passenger and freight transport in Stuttgart is closely linked to the local and national GDP growth. Therefore mobility service demands are likely to increase in the next few years, thus leading to an increased energy demand in the transport sector. This is one of the reasons hindering a fast decarbonization the transport sector, compared to the electricity and heating sectors. Here the CVD forces to intervene and reduce emissions. The minimum procurement targets of the CVD urge bus operators to invest in vehicles with alternative drives. But the high conversion costs can make public transport more expensive. In the future, economies of scale will reduce the acquisition costs for vehicles and infrastructure. But the changeover will be necessary in the next few years before the costs for alternative drive systems align with those of a diesel vehicle. Forecasts show that the change could also take place without a binding directive, but that it would have taken companies longer. Without the CVD, external factors can slow down or prevent the decarbonization (e.g. falling diesel prices).

It remains to be seen whether government subsidies will be able to limit the costs for the transport companies to an appropriate extent. Future studies should focus on the impact of the Clean Vehicle Directive in the European Union.

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Authors

Ms. Daniela Schneider has been going to the Esslingen University of Applied Sciences from September 2013 till August 2017 for her bachelor's degree. From October 2017 till September 2019 she has been going to the University of Stuttgart for her master's degree. She studied "Industrial Management/Automobile Industry" and "Technically oriented Business Administration". At the moment she works as a research assistant at the Esslingen University of Applied Sciences at the Institute of Sustainable Energy Engineering and Mobility.

Ms. Laura Langenbucher has been going to the Esslingen University of Applied Sciences from September 2013 to August 2017 for her bachelor's degree and from September 2017 to August 2018 for her Master's degree. She studied "Environmental Technologies" and "Energy Systems and Energy Management". She wrote her graduation work for TransnetBW a German transmission system operator. She now works as a research assistant at the Esslingen University of Applied Sciences at the Institute of Sustainable Energy Engineering and Mobility. The topic of her work is the optimization and economic evaluation of a renewable powered hydrogen generation unit.

Lukasz Brodecki is a research assistant at IER in Stuttgart since 2014. He graduated in 2012 from the Tsinghua University in Beijing in Automotive Engineering (M.Sc.) and in 2013 from the RWTH Aachen University with a Master of Science in industrial engineering with a focus on renewable energies. His research field includes the modelling of the energy and heat market, the study of impacts of energy-autarky ambitions in municipalities, as well as the model-based scenario analysis and development of energy system models, in particular TIMES Local.

Mr. PD. Dr. Markus Blesl is head of the Department of System-Analytical Methods and Heat Market (SAM) at the Institute of Energy Economics and Rational Energy Use (IER) at the University of Stuttgart. He received his diploma in physics at the University of Stuttgart in 1995 and received his PhD in 2002 with a thesis on spatially high resolution modelling of local energy systems. In 2014 he habilitated with his thesis "Combined Heat and Power in the Heat Market of Germany and Europe - an Energy System and Technology Analysis" and received venia legendi for the subject Energy System and Technology Analysis.

Prof. Dr. Ralf Wörner is head of the Institute of Sustainable Energy Engineering and Mobility since 2018. He became chair professor on the field of vehicle technology in the automotive industry at the Esslingen University of Applied Sciences by the end of 2016. In between of 1997 till 2016 he worked as leading Engineer at Daimler Company, whereof he was in charge for the development activities of powertrain systems applied in international cooperation programs from 2011 to 2016 and of different types of automatic transmissions at Daimler Company from 2007 to 2011.