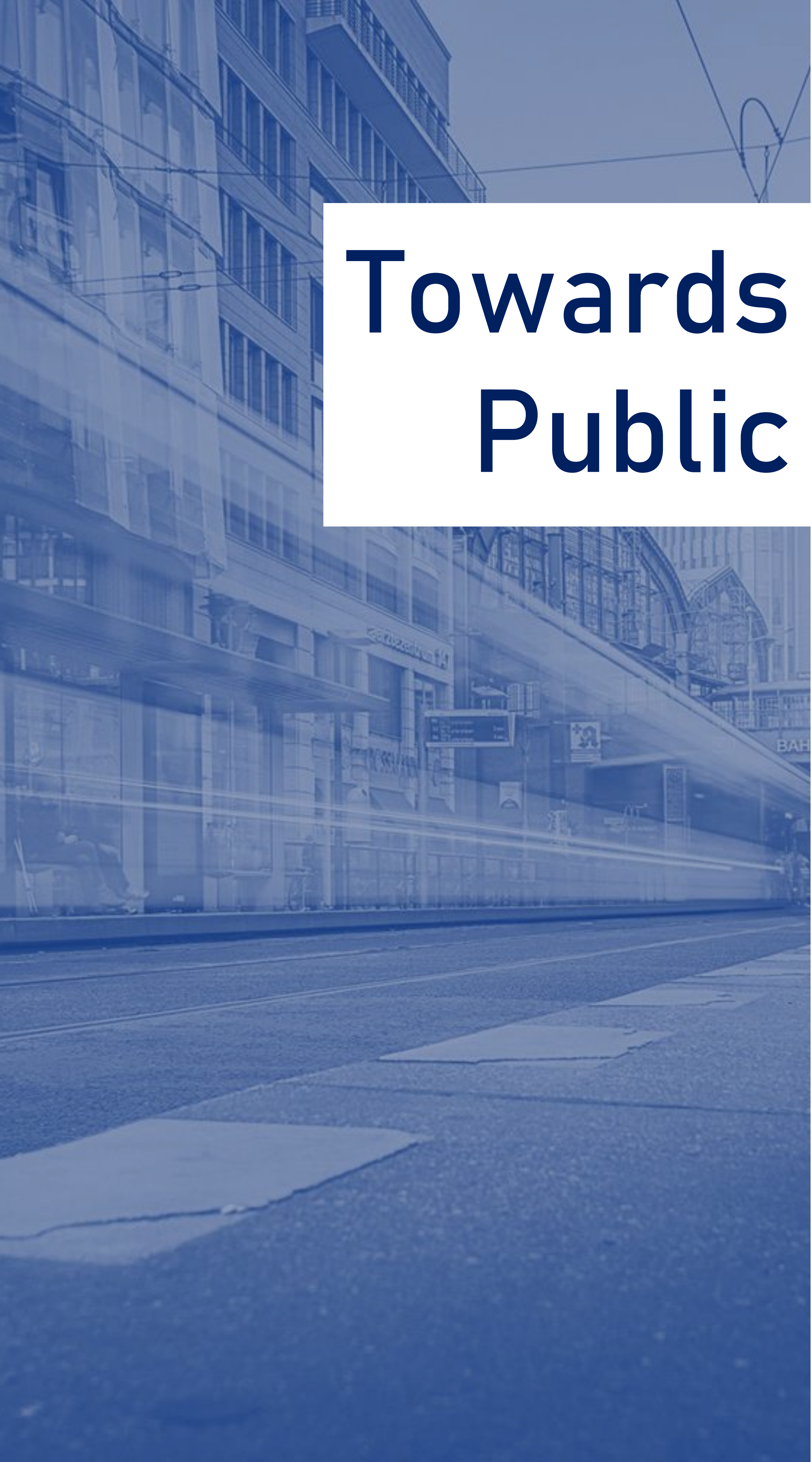

Towards Zero Emission Public Transport

An exploration of the challenge of bus decarbonisation and its pioneering role in terms of climate action and air quality initiatives from the perspective of Europe’s metropolitan transport authorities

EMTA
European Metropolitan Transport Authorities

What's EMTA?

EMTA is the association of European Metropolitan Transport Authorities. It was established in Paris, where the association officially resides, in April of 1998. Over twenty years after its establishment, EMTA now brings together the transport authorities of 30 European metropolitan conurbations. EMTA's member authorities exercise responsibility in planning, integration and financing of public transport and mobility, serving more than 85 million Europeans.

The association's founding members (Berlin, Barcelona, Brussels, Frankfurt, London, Madrid, Manchester, Paris and Vienna) opted to position EMTA as a bespoke and exclusive network for peer-to-peer exchange of know-how, experience and best practices. EMTA works fully independent from transport operators, OEMs and the commercial transport industry and thus allows for very open and honest, yet targeted and detailed discussion among its member authorities.

To continuously enable such discussion, EMTA brings together high-level executives and management personnel of its member authorities twice a year for a general meeting, hosted by a member authority in its respective city or metropolitan area. For further content elaboration, EMTA organizes working groups, collaboration efforts and joint research actions on specific themes and issues, bringing together the respective expert colleagues from the various authorities.

EMTA is governed by a board formed by seven elected member authority executives, who for two years extend their competencies in the management of their respective transport authorities with the conception of EMTA's working program. The program defines the priorities and focal topics that will be address in their board period. EMTA's focus topics for the current board period are decarbonization and air quality, Mobility as a Service Governance, Demand Responsive Transport, and the Evolving Role of Transport Authorities in a multimodal mobility landscape.

Since 2004 EMTA issues its EMTA Barometer, an annual benchmark publication reflecting the state of play in EMTA's member authorities and their respective transport systems. More information on the EMTA website available at emta.com.

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How come we talk about Public Transport Decarbonisation?

The need to decarbonise transport - and thus also public transport - is based on two societal problems which at first glance appear as rather independent challenges: Climate Change and Air Pollution. The source problem behind these challenges is the pollution resulting from the use of the hydro-carbon energy sources coal, peat, oil and gas - referred to as fossil fuels - in industrial processes, for heat and electricity generation, and as propulsion energy-source in transport. Due to a varying scale level and impact, location dependence and target specificity, climate change mitigation and air quality improvement programs have, however, often been considered separately.

Despite such separate consideration, climate change mitigation and air quality improvement deal with two sides of the same coin. The former concerns the global scale: the issue of global warming and climate change as effect of the release of carbon dioxide (CO_2) and other potent greenhouse gases (GHG), like methane, into the atmosphere because of the production and burning of fossil fuels. The later involves the more localized issue of people's exposure to air pollutants like particulate matter (PM10) and nitrogen dioxide (NO_2) in a given area - the majority of which are derived from the burning of fossil fuels in more or less close vicinity to the respective area. Both, the problem of climate change and air pollution issues, thus, largely stem from our current energy model and will exacerbate greatly in the years to come, if no or insufficient countermeasures are taken now.

The reduction and eventually full abandonment of fossil fuels as energy source through the employment of regenerative sources and a more sustainable approach towards energy use – as described by the notion of decarbonisation – is the key lever in the long-term solution to both problems. However, also the accompanying tactical measures required in the short-term, such as emission standards and restrictions, awareness building and education, are to a large degree common to both matters.

EMTA seeks to acknowledge the evident interlinkage between the climate change and air quality debate by recognizing this two-part objective of decarbonisation. The association seeks to achieve an appropriate coordination through a joint consideration of the topics wherever possible and useful. This all the while acknowledging their differences and particularities, to ensure that short-term gains in one matter are not to the detriment of the other or the long-term success of both.

The Air Quality Debate

According to the European Environment Agency (EEA), air pollution is the biggest environmental health risk in Europe, with the effects of exposure to polluted air described as diverse and often obscure. The three most prevalent, damage causing pollutants are particulate matter (PM), Nitrogen Dioxide (NO2) and ground-level ozone (O3).

Subclinical effects of exposure to these pollutants, such as inflammation, often appear gradually and aggravate with continued exposure, leading to continuous damage and many cases of premature death. About 400.000 premature deaths were caused by the exposure to polluted air in the European Union in 2016 alone. On a global scale, the World Health Organisation (WHO) states that 9 out of 10 people breath air containing high levels of pollutants, which kills seven million people every year.

In the European Union, despite improvements in recent years, air pollution remains a major health concern, with the place where one lives substantially impacting the risks one experiences. The EEA states that people in bigger cities with high traffic volume are exposed to the highest concentrations of pollutants.

In densely built and populated areas, dispersion of pollutants is more difficult and slower than in the countryside, hence the greater exposure. This is particularly the case for NO_2, whose main source, road transport vehicles with internal combustion engines, emit it close to the ground and thus close to people.

Air pollution problems are, however, by no means only a big city problem: Local context conditions like the geographic and topographic layout of an area or specific local weather phenomena (e.g. inversion weather) can lead to air quality issues, even in less urbanized regions. Eastern Europe generally shows higher concentrations of particulate matter due to the continued use of solid fuels. Southern European regions with high air pollution rates have even greater risks regarding high concentrations of ozone, as its formation is favoured by sunlight. In metropolitan areas and the surrounding of big cities, such local context conditions can greatly exacerbate generally prevailing pollution issues.

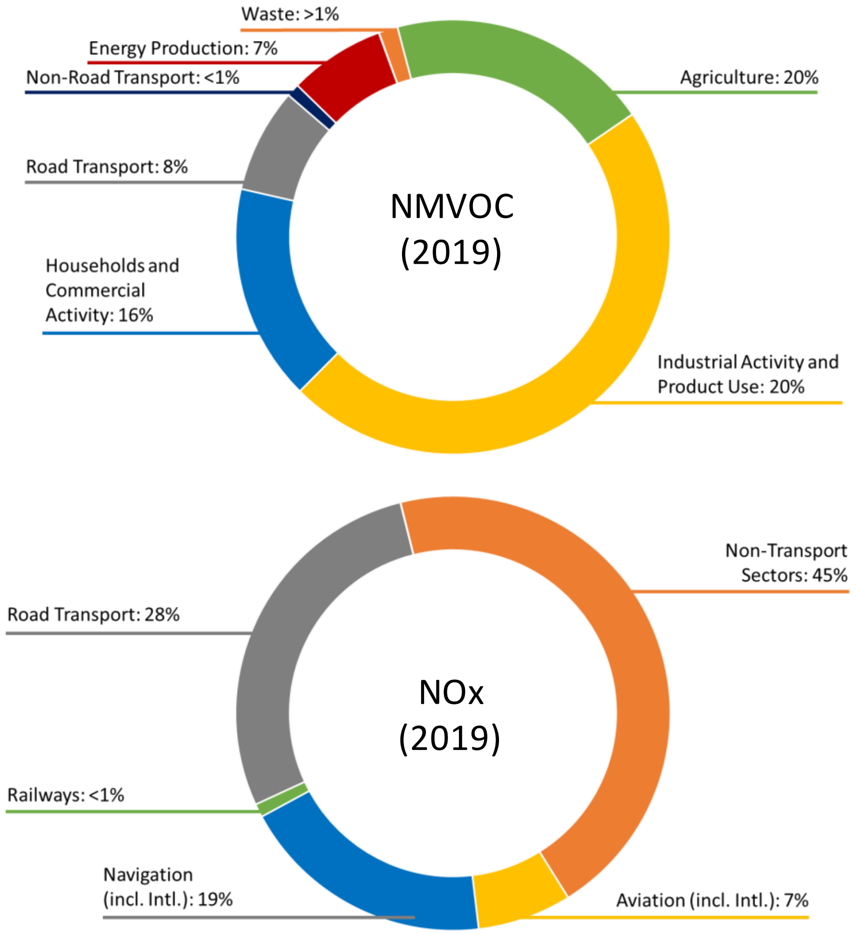
Responsibility for Air Quality in Europe is diffuse and varies greatly between Member States. In most Member states, air quality is a matter of decentralized jurisdiction. Hence it is mostly local and regional governments that are responsible for the majority of the abatement measures of pollutants. At EU level, the Ambient Air Quality Directive 2008/50/EC is considered the cornerstone of Europe's air quality policy framework, as it sets air quality standards for the concentrations of pollutants.

While many EU policies and their national translations have an impact on air quality, which has been improving across the continent in recent decades, they are argued to not yet sufficiently well reflect the importance of improving air quality. This becomes particularly apparent when considering the substantial human and economic cost of air pollution, that is borne by society at large.

The EU's air quality standards were set almost twenty years ago and many are now much weaker than WHO guidelines and the level suggested by the latest scientific evidence. However, most Member States still do not comply with the EU's air quality standards in the first place.

The European Court of Auditors (ECA) argues that the European Commission is too limited regarding the monitoring and enforcement of compliance of member states, leading to frequent breaches of air quality limits.

The ECA furthermore complains that the Ambient Air Quality Directive protects citizens' rights to access to justice less explicitly than other EU Directives: information made available to citizens regarding their access to justice on air quality lacking clarity.



Sector contributions to NMVOC and Transport Sector Contribution to NOx Emissions in EU, 2019.
Source: EEA

The Climate Change Mitigation Debate

After years of efforts by the international community to address climate change, the Paris Agreement was adopted at the Paris Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCC) in December 2015. The Paris Agreement is the first-ever universal, legally binding global climate change agreement.

It sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C – while strengthening country's ability to deal with inevitable impacts of climate change. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century.

After the threshold of ratifications for the Agreements entry into force - at least 55 Parties to the Convention accounting in total for at least an estimated 55% of the global greenhouse gas emission - was achieved on October 5th 2016, the Paris Agreement entered into force on November 4th 2016.

The European Union and six European countries, to which ten EMTA regions belong, were among the group of parties enabling the achievement of this threshold.

The EU's initial determined contribution under the Paris Agreement was the commitment to reduce GHG emissions by at least 40% by 2030 compared to 1990 levels. In December 2020, the EU submitted its updated and enhanced contribution in which the EU and its Member States, acting jointly, are committed to a binding target of a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 levels.

This overall domestic reduction requires emission reduction efforts across all sectors. In 2019, the largest source sectors of the EU's greenhouse gas emissions were the energy industries, combustion of fossil fuels for uses other than transport (e.g. localized heating in buildings, manufacturing and construction, etc.) and the transport sector.

A European Green Deal

To meet Europe's commitments, the European Commission (EC) has put forward a set of policy initiatives that are summarized under the legislative umbrella of the European Green Deal.

The European Green Deal was presented in December 2019. A first central element of the European Green Deal was the European Climate Law that proposed to write the 2050 climate neutrality target into binding legislation. In September 2020, the EC proposed an amendment to the European Climate Law that saw the increase of the 2030 emissions reduction target to 55% compared to 1990 levels. This new target was endorsed by the Parliament and Council in late 2020 and submitted to the UNFCCC as the EU's new Nationally Determined Contribution under the Paris Agreement. With the European Climate Law entering into force in June 2021 the emission targets are now binding European law.

The European Green Deal is described to provide the blueprint for the transformational change necessary to make all sectors of the EU's economy fit for the challenge of meeting the binding 55% emissions reduction target by 2030 in a fair, cost effective and competitive way. The Commission argues that the European Green Deal will at the same time ensure that there are opportunities for everyone, supporting vulnerable citizens by tackling inequality and energy poverty, and strengthening the competitiveness of European companies.

In July 2021, the Commission presented a series of legislative proposals required to deliver the European Green Deal. The package, framed as the 'fit-for-55-package', intends to revise and update EU legislation to ensure that EU policies are in line with the climate targets.

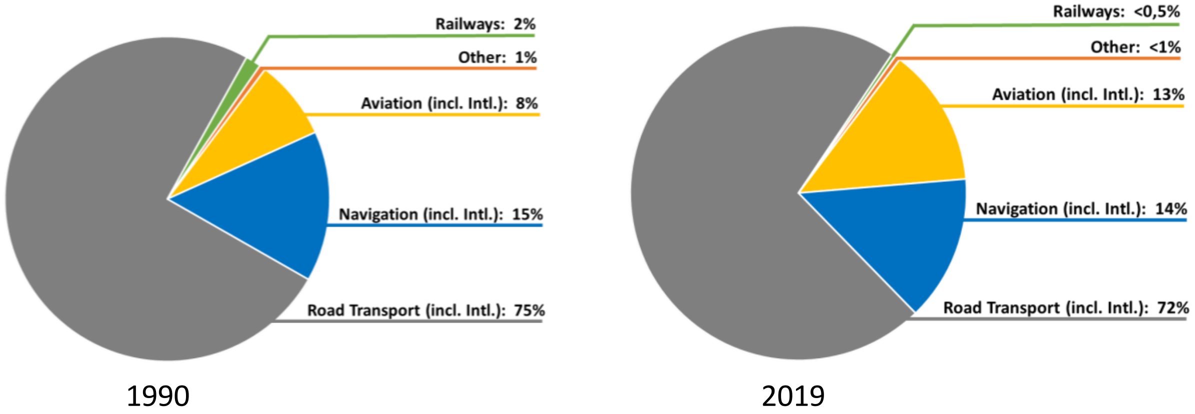
The Relevance of Transport Emissions

Climate change mitigation efforts in Europe are showing first results with a steady, overall reduction of greenhouse gas emissions in the EU in recent years. In contrast to all other sectors, the EU's transport sector has not followed this general trend, with transport related greenhouse gas emissions increasing since 2013. While the rate of increase slows – 2019 saw an increase of 0,8%, the lowest rate in six years – a reversal of the upward trend is not yet in sight.

Where transport represented about 15% of the EU's overall greenhouse gas emissions in 1990, the sectors' relative contribution has increased significantly and will become even more significant with other sectors decarbonising more quickly. Currently, transport represents about a quarter (24%) of the EU's greenhouse gas emissions.

With regard to air pollution, the transport sector significantly reduced emissions of several pollutants compared to 1990 levels (e.g. 40% NOx, above 85% of carbon monoxide, 66% of sulphur oxides, 35% PM10) but is still currently responsible for more than half of all NOx emissions and a proportion of more than 10% of the total emissions of other pollutants. Within the sector, road transport in particular continues to account for a significant proportion of emissions of all the main air pollutants.

Road transport is also by far the biggest emitter of GHG, accounting for about 72% of all transport related emissions (95% even when counting domestic transport only, excluding international aviation and international navigation). In contrast to domestic navigation and railway emissions, which have decreased continuously since 1990, road transport, aviation and international maritime emissions have increased.



Mode distribution of transport related GHG Emissions in EU, 1990 and 2019. Source: EEA

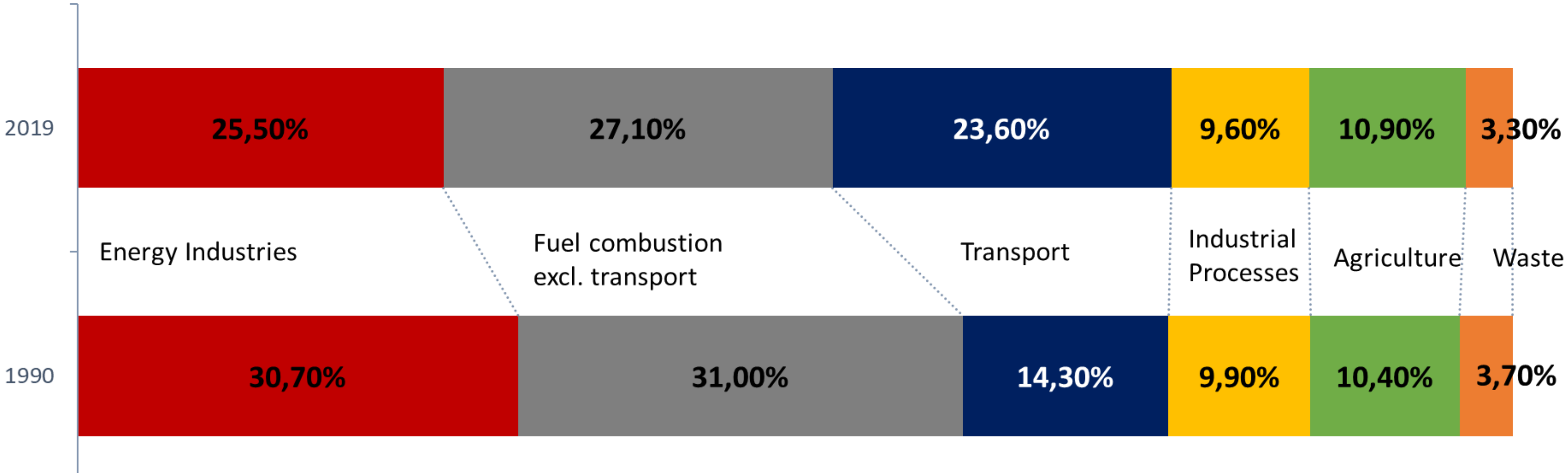
In aviation and international navigation, transport demand is expected to continue to drive emissions upwards in both absolute and relative terms, which in turn reduces the relative contribution of road transport emission to the sectors' overall emissions.

Despite these sector-internal contribution shifts between the various transport modes, the overall transport sector emissions will under the measures currently planned by Member States decrease relatively little from current levels and remain well above 1990 levels in 2030.

The transport sector is thus unlikely to contribute to the emissions reductions needed to achieve the EU's targets for 2030.

Therefore, although action is needed in all sectors, this is particularly important for transport, where all sub-sectors, from the haulage industry and aviation to public transport, need to be much more ambitious if the sector is at all to contribute to Europe's based on commitment in the Paris Agreement

To get Europe's transport sector on an ambitious path to emission reduction, the European Commission developed the Sustainable and Smart Mobility Strategy as part of the European Green Deal. The Sustainable and Smart Mobility Strategy describes eight flagship areas where ambitious changes are necessary to allow Europe's transport sector to contribute to the EU's climate neutrality goal. With the Sustainable and Smart Mobility Strategy, the Commission seeks to achieve a 90% reduction in transport related GHG emissions by 2050.



Sector contributions to GHG Emissions in EU, 1990 and 2019. Source: EEA

Why move to cleaner buses?

Public Transport services only account for a minor fraction of transport related emissions in Europe, both in terms of GHG and air pollutants. Many public transport services, particularly rail-bound services (regional- and suburban-rail, metros, light-rail and trams) are electrified with many PTA's and operators even committing to renewable electricity in their overhead wires and third-rails power supply systems. Thus, decarbonisation of the remaining public transport services - buses and some not electrified rail services – do not come to mind as immediate necessity and most impactful area of transport decarbonisation.

It is, however, not the mere emission volume effect that bus decarbonisation brings to the table but rather the direct market influence and funding share of local and regional authorities.

Due to its clearly regulated organisational structure defined in the PSO Regulation 1370/2007/EU, that establishes a high degree of authority oversight and funding, public transport provides as invaluable springboard for the development and deployment of clean vehicle technology.

While every ton of reduced GHG and pollutant emission counts, especially in local contexts, it is not the direct prevented emissions that drive bus decarbonisation. It is the significant demand for clean vehicles it creates, which kick-starts new and stimulates existing manufacturing and investment in clean propulsion systems that will eventually be deployed in the general vehicle fleets as well. Public transport and other public-sector heavy markets heave to lead by example to spur the necessary investment and innovation for a more sustainable and cleaner transport future

EU Clean Vehicle Directive

It is the realisation that the decarbonisation of public transport and public sector utility vehicles has the potential to become a springboard for wider spread vehicle decarbonisation that forms the rationale for the EU directive on clean and energy efficient road transport vehicles (2009/33/EU) and its 2019 revision (2019/1161) in particular. The revised legislation –referred to as Clean Vehicle Directive (CVD) – seeks to promote clean mobility solutions in public procurement tenders, providing a solid boost to the demand and further deployment of low- and zero-emission vehicles. In other words: using public sector procurement to create a considerable volume demand for clean vehicle technology in order to steer development and investment, increasing supply and industry capabilities that will eventually lead to a widespread deployment of such technologies outside of the public sector's jurisdiction and influence as well.

The new directive was adopted by the European Parliament and Council in June 2019 and applies from 2 August 2021, the deadline for its transposition into national law by Member States (MS). It sets national targets for public procurements of different types of road vehicles by means of purchase, lease, rent and relevant transport service contracting under the PSO regulation (1370/2007). With regard to public transport, the CVD thus applies to both, the purchase or lease of vehicles by a publicly owned transport operator (e.g., a municipal transport operator) and public transport contract awarding by public transport authorities, regardless of the public or commercial status of the awarded operator.

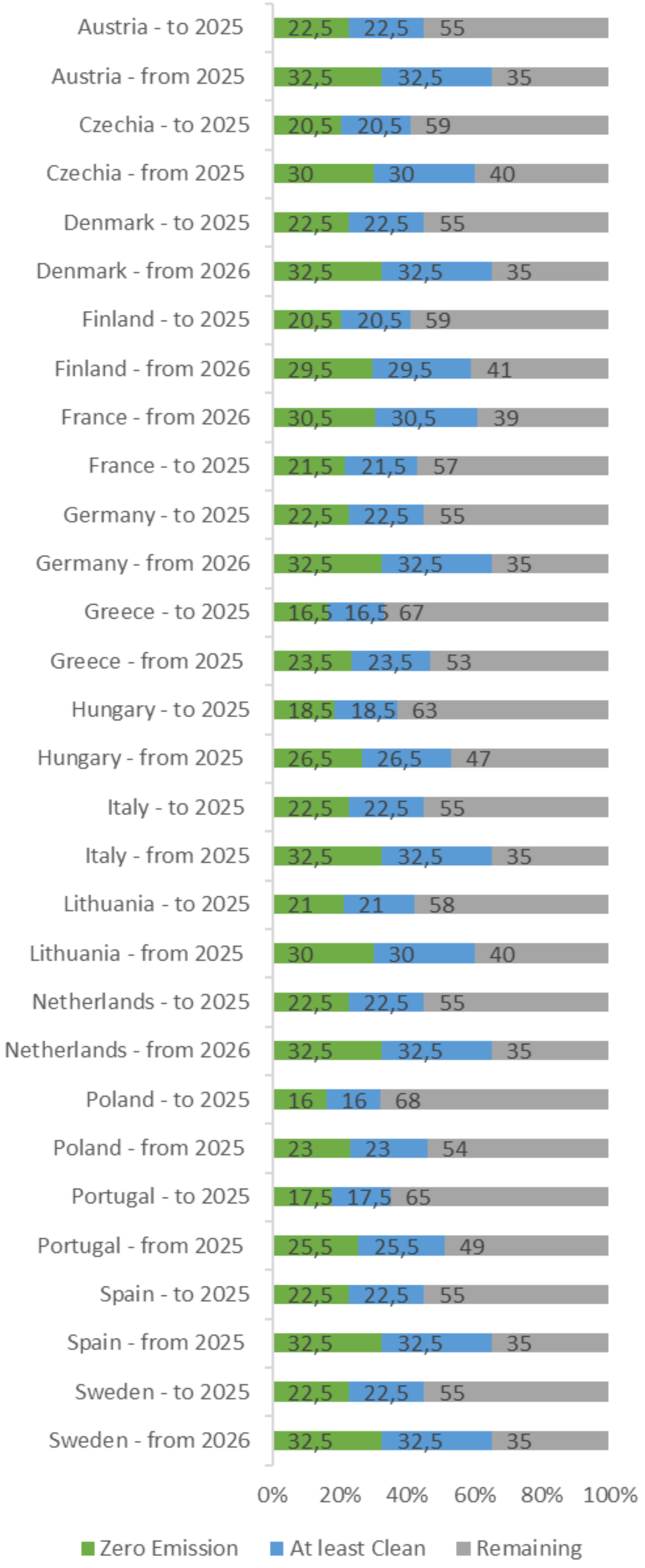
The national targets are set for two periods: Procurement between August 2021 and December 2025 and between January 2026 and December 2030. The targets describe to what percentage public vehicle (or service) procurement must base on clean and zero emission vehicles. For buses in particular, half of the required minimum target for clean vehicles has to be zero-emission vehicles. The targets are calculated on the basis of the aggregate procurement of a Members State, leaving full flexibility to the MS regarding how these targets are to be achieved by different contracting and procurement entities.

The directive clearly defines what a clean vehicle is and differentiates between light-duty (cars, vans) and heavy-duty vehicles. Despite falling in the heavy-duty vehicle category, busses are allocated with peculiar targets that differ between Member States.

The CVD does not apply to all types of buses: Coaches (M3-Class III) and vehicles referred to as 'low-entry-buses' (M3-Class II) are explicitly except. These types of buses are often deployed for express bus services, inter-urban and regional as well as rural bus services. The CVD might thus not apply to a significant part of a PTA's bus network.

Manifesting Public Transport's pioneering role: EMTA 2018 Declaration of Intent

In June 2018, Public Transport Authorities in EMTA, 'realizing that public transport, particularly in urban areas, should be exemplary to drive forward the energy transition of road transport in Europe', committed themselves to 'support the acceleration of "clean vehicles" according to the results of life cycle analysis and to remove local obstacles that could impede or jeopardise the transformation to low and zero-vehicle strategies by procurement of clean vehicles in terms of striving towards 100% of zero- and low-emission bus fleets, as soon as and wherever possible, specifically in densely populated city districts' in the EMTA Declaration of Intent for the promotion of a scaled transition to zero emission buses.



National CVD Targets for buses

In the light-duty category, the CVD consideres vehicles that emit no more than 50g CO_2/km and up to 80% of applicable real driving emission (RDE) limits for NOx and PN are considered clean in the first target period until December 2025. From January 2026 onward only zero emission vehicles – without internal combustion engine – are considered clean. This may be of relevance to transport authorities and operators that organise feeder- or demand-responsive transport services with vans and (taxi-)cars.

Criticism of the CVD evolves around its consideration of fossil natural gas as clean fuel, a lack of consideration of Well-to-Wheel emissions, particularly with regard to synthetic fuels, and a remaining uncertainty regarding the status of the propulsion and fuel systems currently considered 'clean'. A clearer alignment of the CVD and AFID may reduce these risks.

M1
≤ 8 seats + driver
all types

M2	
> 8 seats + driver ≤ 5 tons	
Class A	≤ 22 passengers seated and standing
Class B	≤ 22 passengers seating only
Class I	> 22 passengers seated and standing
Class II	> 22 passengers, seated in principle, allows standing in gangway and an area that does not exceed the size of two double seats
Class III	> 22 passengers seated only

M3	
> 8 seats + driver >5 tons	
Class A	≤ 22 passengers seated and standing
Class B	≤ 22 passengers seating only
Class I	> 22 passengers seated and standing
Class II	> 22 passengers, seated in principle, allows standing in gangway and an area that does not exceed the size of two double seats
Class III	> 22 passengers seated only

Bus categories and bus categories to which the CVD targets apply (green)

What are clean bus systems?

In addition to the definition of the above-described binding quotas for the public procurement of vehicles or transport services, the definition of clean and zero-emission vehicle technologies is the second main object of the 2019 revised Clean Vehicle Directive (CVD) 2019/1161 EU.

According to the CVD, a vehicle of the heavy-duty vehicles category – this includes buses - is clean, if it is propelled with fuels that do not originate in oil production and contribute to the reduction of GHG emissions and environmental compatibility of transport. This definition resonates with the list of alternative propulsion technologies listed in the Alternative Fuel Infrastructure Directive 2014/94/EU (AFID), which are: Hydrogen, Electricity, Gas, Liquid Bio- and Synthetic fuels, and Plug-in hybrids. Hydrogen and electricity qualify as zero-emission propulsion systems and are discussed in the subsequent chapter. The AFID is currently in a process of review, which may impact this list.

Clean propulsion systems

To be considered clean, alternative fuels must be used unblended, which excludes mixtures with conventional gasoline or diesel, and be produced from feedstocks with low indirect land-use change (ILUC) emissions. This is to exclude fuels whose input materials are in a land-use conflict with food production or may risk deforestation. This may lead to scale problems for fuels on biomatter basis.

Biofuels and Synthetic fuels are liquid fuel types, that are in composition comparable with conventional fuels and share a comparable energy specificity, allowing their use as a substitute for Diesel or Gasoline. To produce Synthetic- or Biofuels, Biomass or raw materials like Coal or Plastic-Waste are converted into liquid fuels or Dimethyl-Ether. Fuels produced in gas-to-liquid or power-to-liquid (e-fuels) processes also fall into the synthetic fuels category. While the existing infrastructure for storage, distribution and fuelling as well as existing vehicle fleets could be kept operational with little to no adaptation, the fuel generation process itself is highly inefficient, energy intensive and expensive. In the case of biofuels, land-use conflicts with food production limit the potential for large-scale application.

Synthetic and Biofuels may provide as solution to replace conventional fuels in niche applications in public transports where biomethane or zero emission vehicles cannot be employed due to local context conditions (e.g. height limits of bridges and tunnels) or insufficient driving ranges. Biofuels and Synthetic fuels are, however, argued unfit for replacing mainstream fleets.

Gas (Compressed Natural Gas, CNG) buses use compressed methane. This is a mature technology, used for decades in many cities and regions. Gas as propulsion energy source does not impact operations as vehicle ranges exceed 400 km with passenger capacities identical to diesel buses. Refuelling gas vehicles requires the installation of specialized equipment (e.g. compressors) and gas network connections, which modestly increases depot cost compared to diesel busses. Gas buses are currently at a price level of about 110% when compared to conventional diesel buses. In terms of emissions, when considering the total fuel cycle, CNG buses have slightly lower GHG emissions compared to diesel, despite the emission of some methane during fuel production. With regard to air pollution, gas buses lead to a favourable decrease of NOx (-50%) and particulate matter (-95%) in vehicle exhaust emissions.

Biomethane is a renewable, near-pure methane gas and thus indistinguishable from natural gas. It is produced either by thermal gasification of solid biomass, is captured as by-product from water purification - where it was previously flared - or produced by anaerobic digestion of organic matter (e.g. plants and crop residue, sewage sludge, or agricultural, industrial and household waste) in an oxygen-free environment (fermentation). The raw gas produced is then purified and can be injected into the existing gas network. The cyclical nature of the process, storing carbon in plants before releasing it into biomethane, guarantees the renewable nature of this energy and make it climate neutral. Several life cycle analyses of biomethane in mobility – then referred to as BioNGV - place biomethane buses on an equal climate impact level as battery electric buses.

Zero-emission propulsion systems

The CVD considers a vehicle ‘zero emission’ if its internal combustion engine meets the extremely low emission limit value of 1 g CO_2/km or 1 g CO_2/KWh or does not have a combustion engine at all. Of the list of alternative fuels represented in the AFID, only Electricity and Hydrogen meet this requirement. Unfortunately, Biogas buses are not included in the zero-emission category of the directive: Gas vehicles, even when propelled with biomethane, do indeed produce exhaust emissions surpassing the threshold set in the CVD. However, due to the renewable nature of Biomethane, the total fuel cycle achieves net zero emissions of CO2/km.

Battery electric and Hydrogen Fuel Cell buses are, thus, currently the only systems transport authorities and operators have at their disposal to meet the demand for zero-emission bus transport induced by the over-time increasing percentage requirements in the Clean Vehicle Directive as well as ambitious targets of cities and region that often surpass the CVD requirements substantially.

As the following elaborates, hydrogen is not a mature technology for buses, and electric buses still fail to address all operational needs of public transport fleets. That's why biomethane is still widely considered as renewable bridge technology today until battery electric buses extend their range through developments in battery technology and hydrogen is developed towards market maturity.

Battery electric buses are driven by an electric motor that draws its drive energy exclusively from an on-board traction battery. All battery electric bus systems do not produce any local emissions and can be operated as zero-emission systems entirely, provided the primary energy used to generate the electricity employed in the system stems from renewable sources.

While battery electric buses require more energy during the production process of the system components due to the energy intensive extraction and processing of resources, their operation is highly efficient regarding primary energy efficiency: Electric motors convert about 85% of the supplied energy into motion. In combination with the very efficient energy generation and transmission process of renewable electricity, battery electric bus systems supplied solely with renewable energy can achieve a primary energy efficiency of about 70%.

Electric engines have an additional advantage that further increases their energy efficiency: the recuperation of energy when braking. Once a vehicle is in motion, a significant amount of energy – of the energy required to accelerate the vehicle – can be regained and returned to the battery. Combustion engines cannot recuperate. Any energetic potential of a braking vehicle is thus always lost, regardless of the fuel type (conventional, bio- or e-fuels).

Battery electric bus systems can be subdivided into depot-charging systems and opportunity charging systems by differentiating based on the process of (re-)charging of the traction battery and the technology employed in this process. The two battery electric traction concepts should, however, not be compared against one another competitively but rather be considered to each serve different applications. An opportunity charging system is often not suitable for a bus line with high frequencies and depot charging systems currently offer a range of about 200 km a day, which is not suitable for many bus lines. Furthermore, recycling of electric batteries is an important issue that is not considered today but that may become a major issue in close future.

For a more detailed exploration of the particularities of battery electric bus systems, please refer to the chapter Technical Discussion of Zero Emission Bus Systems at the end of this paper.

Hydrogen fuel-cell electric buses have electric motors that are powered with electricity generated directly in the vehicle by means of a hydrogen fuel cell, where the chemical reaction of hydrogen with oxygen produces electricity. The electricity is then stored in a battery which feeds the electric drive train. To a considerable degree, hydrogen fuel cell vehicles are thus comparable with battery electric vehicles. In the case of hydrogen, however, the battery's dimensions are significantly smaller as it is only required as the intermediate storage, balancing the energetic difference between the fuel cell's capacity and the engine demand at any time. Like in the case of battery electric vehicles, recuperation of break energy is possible, yet in the case of fuel cell buses limited in its potential due to the smaller battery.

Regarding energy efficiency, the electric motor in the hydrogen drivetrain converts 85% of the supplied energy into motion. However, the process of hydrogen production and re-transformation into electricity in the fuel cell comes with a considerable loss of effectiveness: An electrolyser has an efficiency of about 60%; a fuel-cell and battery system in the vehicle has an efficiency of about 55%. The overall primary energy efficiency of a hydrogen bus system based on green hydrogen is therefore only about 26% - which is comparable to diesel buses.

In contrast to the highly efficient battery electric systems, this lower efficiency reduces the systems' potential to offset the more extensive upfront costs for vehicle and infrastructure as well as additional GHG emissions occurred during vehicle component manufacturing during the course of the operation. If green hydrogen is not produced locally but requires transportation, the energy required in this supply chain may further reduce the primary energy efficiency of hydrogen fuel-cell bus systems.

To achieve the intended emission reduction effects, hydrogen employed in zero emission buses has to be so called green hydrogen, that is to say hydrogen produced through electrolysis with renewable electricity. The current supply of hydrogen in the market, however, is largely so-called grey hydrogen, originating from fossil fuel reformation with high GHG emissions. Currently, hydrogen buses are not a mature technology. No manufacturer has so far succeeded to produce hydrogen buses or coaches that meet the high reliability requirements of public transport operation.

For a more detailed exploration of the particularities of hydrogen fuel-cell bus systems, please refer to the chapter Technical Discussion of Zero Emission Bus Systems at the end of this paper.

Bus decarbonisation in practice

With conventional diesel bus systems, the fuelling infrastructure and bus operation may be considered separately of one-another since bus operators can easily rely on established structures and supply chains of the energy sector. The widespread availability of fuel either through established delivery models to bus operator's depots or at standardized fuel station and the relative speed with which refuelling takes place, has allowed for an immense flexibility in route and vehicle scheduling. A vehicle's driving range has likely never been a necessary condition, let alone a sufficient condition for the design of a bus route and its operations.

With zero emission bus systems, the relative newness of the employed technologies and the lack of established fuel infrastructure (considering both, the supply chain of green hydrogen and provision of electric charging infrastructure) leads to considerable component dependencies between rolling stock and charging/fuel infrastructure which is also reflected in the cost structure of zero emission bus operations.

Costs of zero emission bus operation

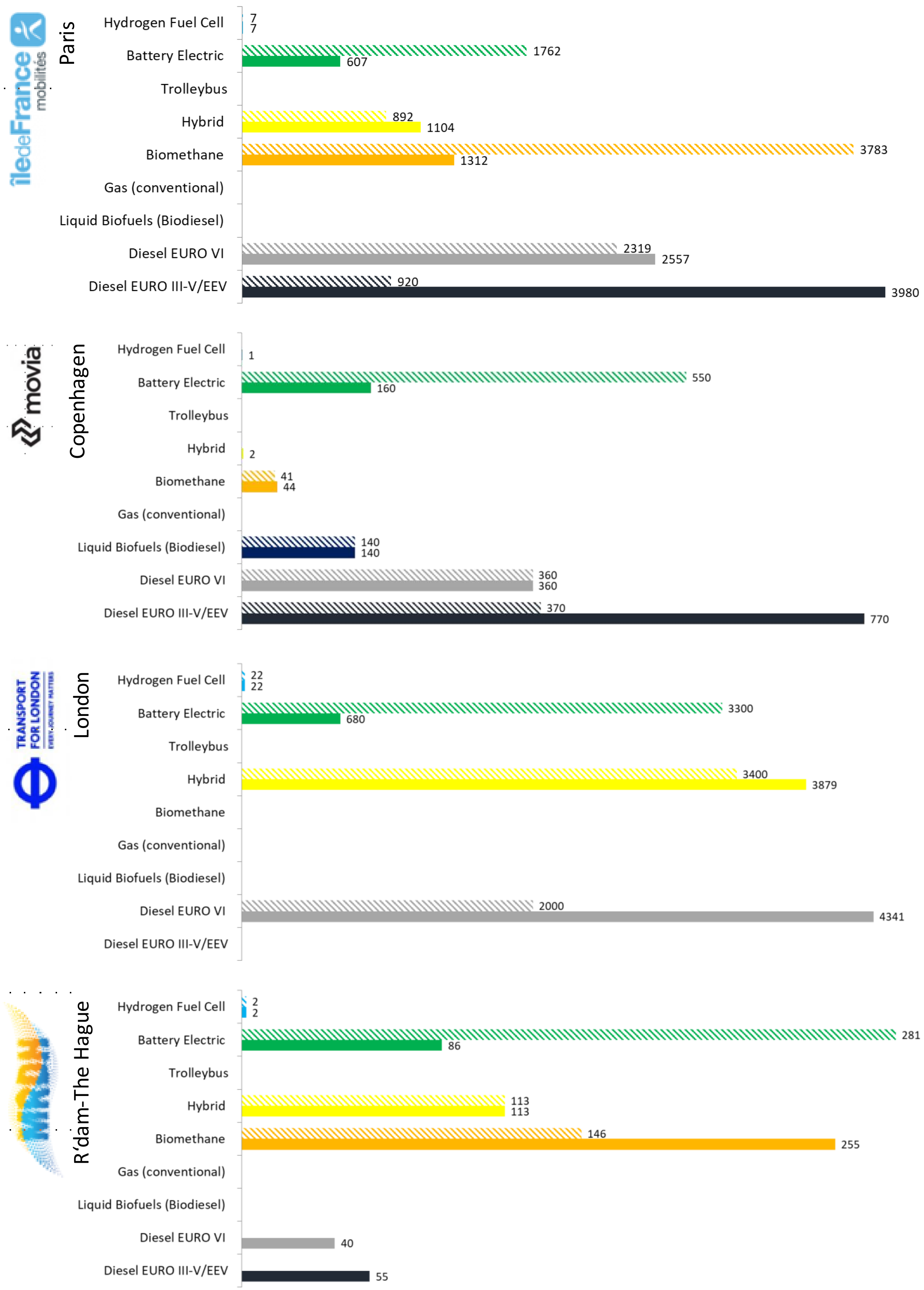
As introduced above, zero emission bus systems require a complete consideration of the components related to vehicles and fuelling infrastructure, and their respective operational cost. The cost structure of zero emission bus systems thus differs significantly from conventional bus systems and includes the following component categories: capital cost related to vehicle investment, vehicle maintenance costs, energy costs, and infrastructure costs, which includes investment and operation costs in the required infrastructure components. In the total system cost, personnel and administration or overhead costs need to be added. It may, however, be expected that these cost factors do not lead to additional system cost of a zero-emission bus system compared to a system with conventional buses and are thus not considered explicitly in the following.

Vehicle investment costs concern the capital expenditure involved in the purchase of the vehicles. For a standard battery electric buses, these capital costs are currently at about 215% of the level of conventional buses. In the case of hydrogen fuel-cell vehicles, a level of about 250% is currently realistic. Battery electric vehicles have shown considerable price decreases, mainly driven by price reduction for batteries. Battery prices are expected to reach year-on-year price reduction levels of 9-12%, if demand in Europe develops favourably. Hydrogen fuel-cell bus prices have long plateaued at a high level, but a slow price decrease is now visible.

Despite high uncertainties remaining about the actual potential of economies of scale, vehicle manufacturers confidently specify the target price of the coming years about 15% below current price levels. Vehicle investment costs for hydrogen buses would then roughly correspond to the current prices of battery electric buses.

Infrastructure investment costs concern the capital expenditure as well as the maintenance cost associated with the charging or fuelling infrastructure components. This concerns charging infrastructure in depots and opportunity charging structures, where applicable, for battery electric buses. In the case of hydrogen, hydrogen fuel station(s), electrolyser(s), storage and compressor equipment is considered. Alternative fuel infrastructure maintenance cost arguably amounts to about 4% of the investment cost of the respective infrastructure annually. This cost factor also includes the cost associated with a connection to the electricity grid as well as grid fees. Infrastructure investment cost amount to about 12% of the total system cost in the case of battery electric buses and 17% with hydrogen fuel cell buses. Infrastructure investment and maintenance are not considered for conventional diesel operations as the cost of the well-established supply chain of petrol, including the potential cost for a petrol station, is reflected in the diesel price and thus the energy cost factor. For comparison: The additional infrastructure investment cost associated with Gas buses (and thus also biomethane buses) amounts to less than one third of the infrastructure cost associated with battery electric buses.

Cost of operation concern the cost for energy and maintenance incurred during the time operation. In the case of battery electric buses, it is argued that a large proportion of the higher capital costs for the vehicles may be mitigated by much lower operational costs. This is achieved through lower general maintenance costs for electric drive trains, the high primary energy efficiency, but especially through lower energy cost for electricity:



Bus fleet composition in selected EMTA Metropolitian Areas:

SOLID 2021 actual fleet data

HATCHED 2025 non-committal projections

The energy cost incurred with battery electric buses is about 52% lower compared to diesel combustion. An 8-year total cost of ownership analysis, comparing battery electric and diesel operation finds that the tipping point, where electric bus operations becomes cheaper than conventional diesel bus operations has already been reached.

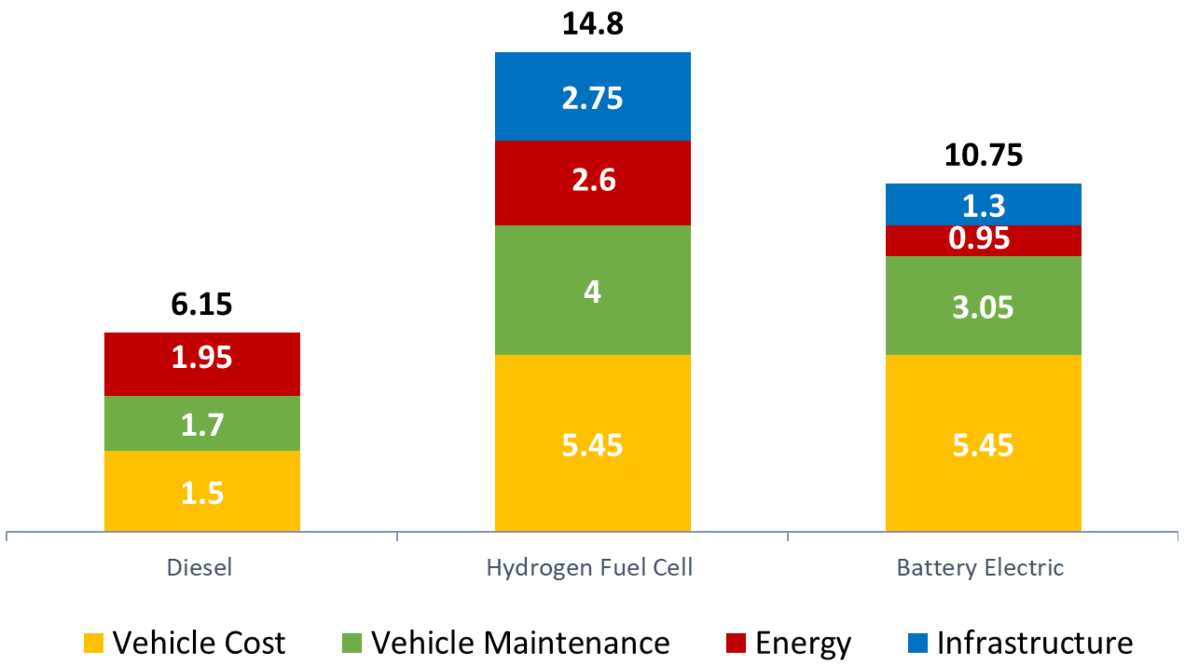
In practice, however, great uncertainty remains regarding the actual operational cost of zero emission vehicles, due to a potential need for replacement of expensive battery or hydrogen fuel-cell drive trains during the lifespan of the vehicle. In addition, the required adjustments in depots and workshops, which may need to include cranes for working on components situated at the roof of vehicles, detectors, and safety equipment is reflected inadequately due to a remaining lack of experience. In the case of hydrogen, the offset potential of the higher capital costs during the course of operation is limited at best. This is due to the low primary energy efficiency of hydrogen fuel-cell vehicles and the more complex and expensive hydrogen supply chain. Energy costs for hydrogen need to reflect the energy used for the electrolysis, compression, and storage of green hydrogen as well as energy required for a potential transport to the site of operation and may thus exceed energy costs of conventional diesel operations by up to 35% in current market conditions.

In an anticipatory scenario that does consider these operational uncertainties, vehicle maintenance costs for electric buses are expected about 80% higher compared to conventional buses. In the case of hydrogen fuel cell buses an increase of 130% is expected. This substantial cost increases stem mainly from the high-risk premiums for the exchange of components during the vehicle's lifespan and may be significantly reduced with growing experience of such long-term maintenance efforts at the side of vehicle manufacturers.

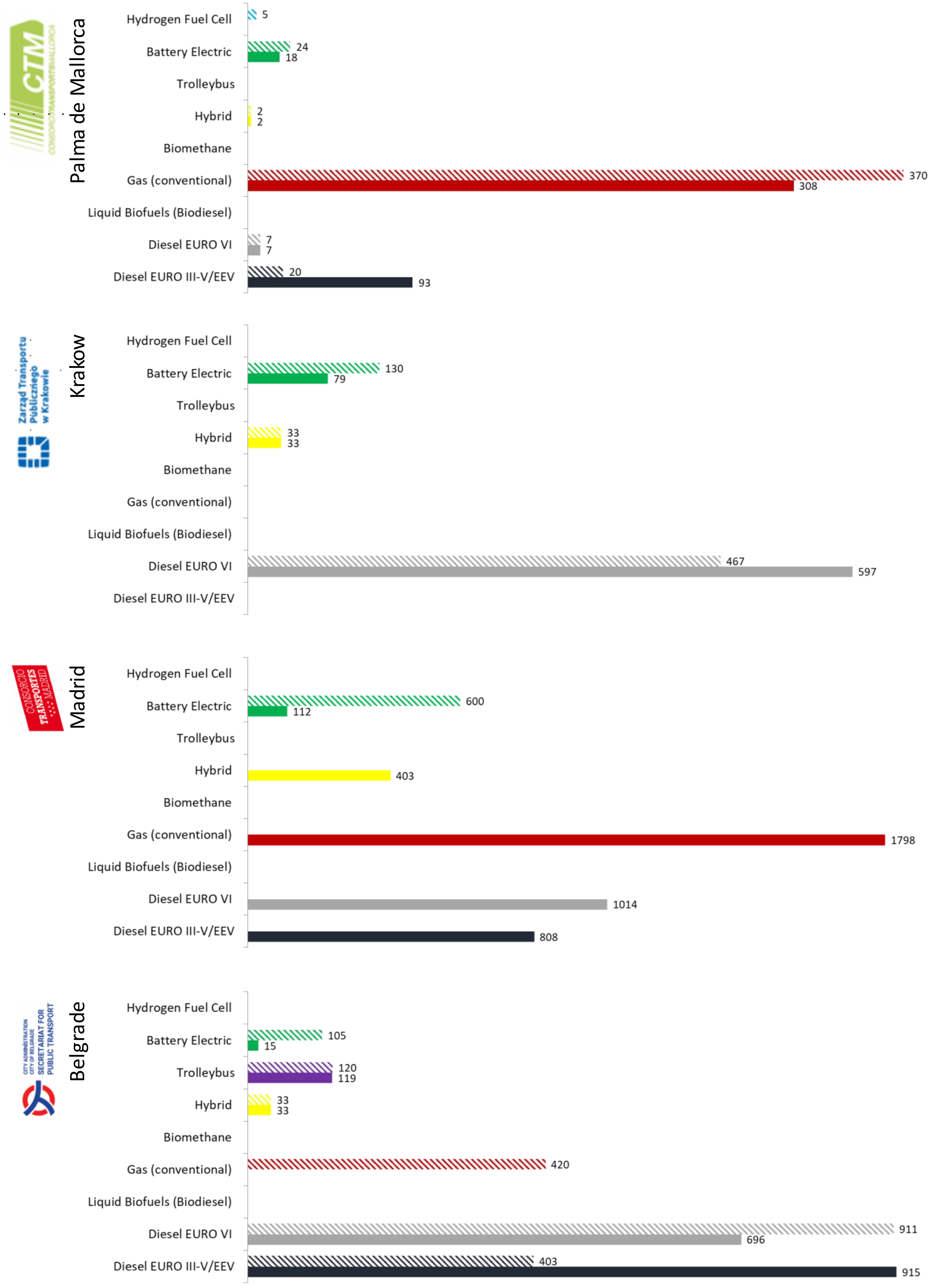
With the number of vehicles kept equal – which may provide a challenge particularly regarding the lower ranges of battery electric buses – an anticipatory estimation that considers currently realistic risk premiums (e.g. for exchange of components) total system cost for 15 years is for hydrogen fuel cell bus operation 154% and battery electric bus operation 74% more expensive than bus operation with conventional diesel buses.

Total cost of ownership analyses induding externalities, according to researchers and advocacy groups, allow controlling for flaws of a purely operational cost consideration. Pure operational cost consideration neglects the positive effect of zero emission bus operation on transport related externalities.

If the external cost associated with air-pollution, noise and GHG emissions - currently borne by society at large - is reflected, battery electric buses already offer a better total cost of ownership and are roughly on parity if only health costs associated with air and noise pollution are considered. This analysis however, bases on an eight-year comparison, in which no need for component exchange is assumed, with a daily distance favourable to the capacity of current battery electric buses. Nevertheless, this analysis shows that the quantifiable benefits of zero emission buses to society alone already outweigh a substantial part, if not all, of the additional costs of the operation.



Estimation of total cost per year for a generic bus service area with 100 vehicles in million euro. expected vehicle life-time of 15 years with exchange of battery/fuel-cell & battery expected.
Based on calculations of KCW for Low Carb Project.



Bus fleet composition in selected EMTA Metropolitian Areas:

SOLID	2021 actual fleet data
HATCHED	2025 non-committal projections

Issues that remain

Although transport authorities and their regions and cities as eventual owners of the public transport systems in Europe are committed to playing their part in decarbonisation, with many having established decarbonisation objectives and time-lines much more ambitious than the targets defined by the Clean Vehicle Directive, great challenges remain that limit transport authorities' ability to deliver.

Mismatch of operational requirements and capabilities of zero emission bus systems

Despite the more widespread application of zero emission buses throughout Europe, many operational requirements of bus lines and networks are still not met by zero emission systems, particularly battery electric buses. In some cases, this lack of capabilities regarding the range of vehicles can be circumvent by utilizing sometimes significantly larger fleets, where the additional vehicles compensate for the time required for intermittent charging. This solution, which obviously imposes additional costs, is not feasible everywhere, however. Regional and rural bus services where vehicles cover substantial distances in difficult topographical conditions in one turnaround but also urban routes – operated with vehicles subject to CVD mandates – with short stop intervals and frequent acceleration and potentially limited space for charging infrastructure, cannot be decarbonised with existing battery electric systems.

Hydrogen fuel-cell buses, that would resonate with such complex route conditions, have not yet reached market maturity.

Where hydrogen buses are deployed currently, operators suffer from low availability rates, high costs and the complex, far from established supply chain of green hydrogen. These difficulties are exacerbated by regulatory unclarities. For example, it remains disputed whether hydrogen produced through electrolysis based on grid electricity of unknown origin can be "greened" with renewable energy certificates. Should hydrogen only be considered green if directly produced from a known renewable energy source, production of green hydrogen at or near depots of hydrogen fuel-cell buses – which is favourable regarding the elimination of transport movements and some storage of the fuel – would be largely impossible.

Great efforts remain necessary to further develop battery electric systems and achieve acceptable readiness of hydrogen bus systems.

Development of zero emission bus system manufacturing

The European market for zero emission buses is quickly ramping up. The year-on-year number of electric bus orders about doubled since 2017, with electric buses reaching an estimated market share of about 9% in 2018. While the demand for fuel-cell buses is far behind such development, due to the still lower market readiness of the technology and the green hydrogen supply chain, increasing demand tendency – long before the CVD came into force - shows that transport authorities are serious about taking responsibility with regard to decarbonisation,

Despite this clear development towards main-stream application, incumbent bus manufacturers have been slow in meeting their announced commitments and have to seriously step up their up their game.

EMTA, together with other transport stakeholder organisations have illustrated this need for development at the side of bus manufacturers to the European Institutions in several conversations and correspondences. With the start of series production among many European manufacturers in 2019 and 2020, an important step is taken. Nevertheless, manufacturing capacity still appears insufficient, with delivery lead times for some vehicle batches reaching a disproportionate 18 months. Next to production capabilities, manufacturers need to grow experience and share information regarding the need for exchange of electric drive train components during the life-span of vehicles to allow for accurate cost estimates and planning security.

While delivery lead times for charging infrastructure components are less severe, the market still appears to struggle with niche characteristics: Manufacturers of charging infrastructure are limited and manufacturers are slow in developing useful turn-key or as-a-service solutions that could greatly reduce complexity for transport authorities and operators alike.

Price development for zero emission vehicles

Despite the continued price decrease of battery electric buses, mainly driven by decreasing prices for batteries as main cost drivers of electric vehicles, and the recently noticeable price decreases for hydrogen fuel-cell vehicles, prices for zero emission vehicles are still too high and price development lacks behind expectation. EMTA and other organisations have indicated to the European Institutions before, that the increasing demand volume for zero emission buses fails to deliver the expected price cuts from industry. Manufacturers must develop towards more competitive prices and the European Commission must ensure that manufacturers do not adjust or distort price development to a potentially increasing level of subsidies.

Insufficient structural funding and financing opportunities

Public transport decarbonisation as pursued in Europe is a structural transition that impacts the entire supply chain of bus services and associated assets. With the CVD, the EU further reinforces this structural character as it mandates the technological replacement of a significant percentage of bus operations. Despite this structural characteristic of the programs and objectives, funding and financing mechanisms remain project- and case dependent and thus fail to match the structural financial support needed for successful execution of this effort.

The project-dependent, case by case approach to financial support goes along with complex and time-consuming application processes and essentially establishes a competition between various decarbonisation initiatives for the funding opportunities that all of these initiatives generally and structurally require to be viable in current market conditions.

It is of vital importance that the EU institutions back the structural obligation for the purchase of zero emission bus services and associated assets with structural financial support rather than apportioning the substantial cost differences to cities, regions and transport authorities. EMTA and other stakeholder representatives have continuously indicated this need for more progressive decarbonisation financing. New mechanisms from traditional funding institutions, like existing EU grants (CEF, ERDF and Cohesion Fund) and new instruments (e.g. EU/EIB Blending facility) need to be developed and made accessible for transport authorities, essentially the problem owners of public transport decarbonisation, with lowest possible bureaucratic barriers on a structural basis.

Detrimental budget competition

The lack of structural mechanisms to funding or financing of the considerable cost difference of zero emission bus systems in connection with the clear obligation to the procurement of these systems may force transport authorities to consume budgets to transition existing service patterns to zero emission operations rather than using this budget to invest in new public transport connections, increased frequencies, and greater service levels. Such budget competition is detrimental to the overall cause of transport decarbonisation, as the modal shift away from automobiles towards collective travel, which is promoted and induced by better, more frequent and widespread available public transport services, provides a far greater volume reduction of GHG and pollutant emissions – even if these additional services are produced as conventional diesel services – compared to the purely technological transition of existing services towards zero emission systems. The sector's frontrunning role regarding zero emission vehicles must not risk jeopardizing investments in infrastructure, capacity and service levels that are necessary to ensure public transport can be the envisioned backbone of smart and sustainable mobility.

Financial support coupled to asset ownership

The vast majority of zero emission vehicle subsidy, grant- and financing programs made available by European Institutions and Member States are aimed at the legal owner of the asset. In many cities and regions in Europe, vehicles are in the ownership of transport operators that receive their business through the awarded service contract from commissioning authorities. Due to the relative uncertainty (to receive business or not), operators can only place an order for vehicles and apply for funding and financing programs once the contract is awarded. This creates several issues: When preparing a bid for a service contract tender, operators do not know whether they will receive grants or specific financing and cannot consider these in their bid. Operators need to apply for subsidy after contract awarding, which further exacerbates lead-time requirements between contract awarding and start of operation and places the complex administrative burden associated with an application for funding on transport operators. Smaller and medium-sized transport operators are likely unable to match this burden, potentially leading to further consolidation in the bus operator market which reduces competition.

Decoupling financial support from asset ownership and enabling the contracting authorities to receive funding and specific financing for the price difference in service procurement instead solves these issues. Authorities would know at the start of a tender process what grants and financing conditions they receive, which would then guaranteed be available to the operator awarded with the contact – via the authority. This reduces complexity, lead times, price uncertainties and increases flexibility for transport authorities and furthermore enables shifting from upfront payments to payments aligned with the longer durability of zero emission bus systems.

While asset ownership at the side of the transport authority is a theoretical solution to this issue as well, this is not an option for the many transport authorities that are required to operate an asset-light business model.

Hidden additional workload and overhead costs

Zero emission bus operation leads to an immensely increased workload and additional overhead and risk costs at the side of transport authorities and contracted operators. Costs associated with the capacity building regarding the different planning requirements for zero emission operation and their execution in a service tender, funding and financing requests, negotiations with new stakeholders to the market (e.g. energy grid operators) and the organisation and execution of the actual tenders (which may require separate procedures for service contracts, vehicles and infrastructure) are substantial and entirely borne by transport authorities. The significant cost factors are often hidden in the overall cost structure of the respective organisations and need consideration in subsidy, grant- and financing programs, especially now at the beginning of the transition where uncertainty and associated risks are particularly high.

Need for strong transport authorities as essential tool for decarbonisation

The public transport sector, that is the transport authorities, transport operators and the bus manufacturing industry have been able to build up very efficient service tender and operation processes based on diesel bus technology over the last decades. With alternative fuels, these accustomed processes and relationships need to be adjusted and require significant institutional innovation: Tender processes suddenly concern more stakeholders (e.g. electricity grid operators, energy producers, land owners and local approval authorities for potential infrastructure requirements) and bus system implementation projects have more critical milestones to achieve (e.g. on time vehicle delivery, on time infrastructure delivery, timely connection to the appropriate electricity grid) which require more intense orchestration. Also, the assets concerned with zero emission bus systems are more expensive and have a longer lifespan, which is more difficult to reflect in current transport service contracting practices and require an orderly transfer in case of a change of contracted operator.

Given their technical and planning experience and their central role as integrator of various modes of transport and infrastructure, their knowledge of local context specificity, their clear mandate for public transport procurement and their legitimacy through elected officials, public transport authorities are best positioned to play the instrumental role of coordinating the transition towards zero emission public transport. PTAs are essential to impulse the dynamic for public transport decarbonisation and to manage the financing of the various components involved. That is why public transport authorities should be recognised and clearly mandated by European regulation and national laws as the leading authority for local transport decarbonisation and sustainable mobility efforts in our regions and metropolitan areas.

Extraordinary budget pressure due to COVID-19 Pandemic

The COVID-19 pandemic and accompanying health measures had a strong impact on the finances of PTAs throughout the continent. With budgets under pressure, PTAs are increasingly in the situation where prioritization of investments plays a role. Due to their clear mandate to ensure public transport service operation at useful and competitive service levels, investments in service-relevant assets and service-level increases that promote a modal shift towards public transport may have to be prioritized to the detriment of decarbonisation initiatives. To enable adequate investment in both, network enlargement promoting modal shift towards sustainable mobility and decarbonisation of the very services in the network, it is of upmost importance to find a solution to the extraordinary financing crisis brought about by the pandemic. While European and national funds and financing structures are of great necessity to bridge the price difference for clean and zero emission operations, public transport authorities will eventually have to execute the efforts and finance their share of decarbonisation, which requires healthy budgets in the first place.

Resulting Necessary Actions

To address the pressing issues that remain, National States and the European Institutions, particularly the European Commission:

- have to more strongly address and support the development of zero emission buses and their associated fuel infrastructures that meet the operational demands of Europe’s transport networks.
- have to invest in development of hydrogen propulsion technologies, which are not yet mature for buses, and may not maturate without significant additional investment.
- have to recognise the environmentally damaging nature of current (mostly grey) hydrogen supply, invest in the establishment of a productive supply chain of green hydrogen, and clarify the regulatory and environmental status of hydrogen produced through local electrolysis from grid electricity with renewable energy certificates.
- have to consider including biomethane as a zero- emission technology for buses, as long as hydrogen fuel-cell vehicles are not a reliable and mature enough technology for buses and green hydrogen supply remains unavailable.
- have to manage the essential issue of battery recycling.
- have to recognise the unique position of public transport authorities in Europe’s regional settings and provide them with the required capacities to manage the transition by providing them with a clear mandate as the leading authority for public transport decarbonisation and sustainable mobility in our metropolitan areas at large.
- have to recognise the need for structural financial support in this transition and introduce accessible funding and financing mechanisms that recognise not only the price difference for clean and zero emission bus systems but also the hidden additional workload and overhead cost incurred, to enable transport authorities to achieve the objectives declared at the European and national level.
- have to help public transport authorities to find solution to the financing crisis of public transport resulting from the COVID-19 pandemic.

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The effort brought together experts from various EMTA member authorities for a focused discussion.

This discussion paper has been produced in conjunction with studies, strategies and implementation plans created by respective EMTA member transport authorities.

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Zero Emission Bus Systems –

Technical Discussion

1. Battery Electric Buses

A battery electric bus is driven by an electric motor and, like an electric car, draws its drive energy exclusively from an on-board traction battery.

All battery electric bus systems do not produce any local emissions and can be operated as zero-emission systems entirely, provided the primary energy used to generate the electricity employed in the system stems from renewable sources.

While battery electric buses require more energy during the production process of the system components due to the energy intensive extraction and processing of resources, their operation is highly efficient with regard to primary energy efficiency: Electric motors convert about 85% of the supplied energy into motion. In combination with the very efficient energy generation and transmission process of renewable electricity, battery electric bus systems supplied solely with renewable energy can achieve a primary energy efficiency of about 70%.

Electric engines have an additional advantage that further increases their energy efficiency: the recuperation of energy when braking. Once a vehicle is in motion, a significant amount of energy – of the energy required to accelerate the vehicle – can be regained and returned to the battery. This effect is particularly noticeable in hilly terrain, where a substantial amount of the energy required to get the vehicle uphill is regained during the decent. Combustion engines cannot recuperate, hence, the energetic potential of a braking vehicle is always lost reducing the overall primary engery efficiency of systems with combustion engines – regardless of the energy source (convenitional, bio- or e-fuels).

Battery electric bus systems can be subdivided into depot-charging systems and opportunity charging systems by differentiating based on the process of (re-)charging of the traction battery and the technology employed in this process. The various resulting battery electric bus concepts each have their operational specificity.

1.1 Depot Charging

In the depot- or overnight charging concept, the vehicles are supplied with the energy required for operation during long operational breaks, usually during the night. A major advantage of the overnight charging concept is that a relatively low charging power may be employed as charging may take some time, which extends battery live and allows the use of cheaper infrastructure components – both resulting in a cost saving effect.

The range of a battery electric bus with depot charging is determined by the size of the battery, with the unfortunate effect that batteries get heavier if increasing size. Vehicles with batteries that permit a long rage thus become very heavy, requiring more energy for acceleration of the vehicle. Most manufacturers appear to have troke a balance between battery size and weight for their vehicles that relates to a realistic driving range of about 200 to 250 kilometres. At least that is the range of most models of depot-charge buses currently offered in serial production. It is expected that this equilibrium range will further increase with the continued development of lighter, yet more powerful battery cell technology. First depot-charge models are reportedly operating 500+ kilometres on a single charge.

The range of a battery electric vehicle is also strongly impacted by the use of auxiliary systems, like heaters and air conditioning. To increase the range, diesel-powered additional heaters are often still installed. Under favourable circumstances, like a year-round mild climate, ranges may thus be significantly greater already without the use of diesel auxiliaries. With further development of technology regarding heat pumps, electrical heating and cooling will become more energy efficient and reduce the impact of weather conditions on battery capacity. This results in the realistic ranges of battery electric buses becoming longer and more consistent throughout summer and winter times.

1.2 Opportunity Charging

In the opportunity-charging concept, vehicles are supplied with the energy required for operation at fast-charging stations either along the route they are servicing, exclusively or in combination with overnight charging at the bus depot.

The opportunity charging concept may thus be employed twofold: Charging a vehicle along the route of its service in addition to overnight charging at the depot – as a concept to extend the range of the vehicle. Or charging the vehicle more or less exclusively along the route in order to reduce the size of the battery necessary in the vehicle – as a concept to reduce the cost of the rolling stock.

Opportunity charging concepts can be subdivided into two categories based on the location where and the speed at which charging takes place: Terminus-charging describes an opportunity charging concept where vehicles are charged for several minutes at a terminus stop of a line or another turnaround place (e.g. a place where drivers may take a break). The battery is recharged - or rather topped up - with chargers of up to 300 kW before a new line course commences. For this either a pantograph that is attached to the vehicle moves up to the charging post, or a charging arm moves down from the charging post to the vehicle.

Flash-charging is an opportunity charging concept where vehicles are charged at several ordinary bus stops along the route for a very short time each. This concept uses chargers of up to 600 kW to provide the necessary power boost in the very limited time – sometimes just 15 seconds - of passenger exchange at the bus stop. This flash-charging concept therefore requires a pantograph or charging arm that can extend towards the charger (or vehicle – dependent on the type of infrastructure) with considerable speed. The short but frequent charging along the route allows the batteries of flash charging systems to be very small in size, reducing the space used in and weight of the vehicle.

A third opportunity-charging concept is related to the proven trolleybus technology. Trolleybuses are electric buses that – other than battery electric buses – receive the required drive energy from overhead wires.

Original trolley buses require a constant connection with this overhead wire. The power supply infrastructure thus defines the possible routes trolley buses can drive. When equipping vehicles with both, a trolleybus pantograph and an on-board traction battery, this creates an interesting hybrid: When driving on roads with overhead wires, the vehicle uses this energy provided through the overhead wires for traction and charges the battery. Once the overhead wiring stops, the vehicle continues its journey with energy from the battery, that is again recharged once the buses re-enters a stretch of road with overhead wires. The trolleybus-battery hybrid may be useful in situations where trolleybuses already exist – to extend services without the need for enlargement of the power supply infrastructure – or where several bus routes interline in a form of trunk line for a considerable distance, where newly to be installed overhead wiring could be a cost-effective solution to charging vehicles operating on the various lines.

Another linked case is the use of existing overhead wires of tram systems for opportunity charging of buses. However, as tram vehicles use the rails in the ground as second electrical pole in addition to the single overhead wire, charging buses in motion along the existing infrastructure is not possible. Nevertheless, the concept is currently employed for charging standing vehicles at specific locations, where the second electrical pole is provided in the form of a second overhead wire in addition to the existing wire of the tram system.

2. Hydrogen Fuel Cell Electric Buses

Hydrogen powered buses have electric motors that are powered with electricity generated directly in the vehicle by means of a hydrogen fuel cell. In the fuel cell, electricity is created through the chemical reaction of hydrogen with oxygen. The electricity is then stored in a battery which feeds the electric drive train.

To a considerable degree Hydrogen fuel cell vehicles are thus comparable with battery electric ones regarding their electric drivetrain that receives its energy from a battery. In the case of hydrogen, however, the battery's dimensions are significantly smaller as it is only required as the intermediate storage, balancing the energetic difference between the fuel cell's capacity and the engine demand at any time.

When dimensioning the hydrogen drive train, the service area characteristics need to be taken into account thoroughly. In the case of mountainous topography, the battery's discharge capacity must allow for continued intense discharge during longer ascents without risk of overheating. The battery must furthermore provide enough storage to act as a buffer during challenging stretches of a route: Continued retrieval of the entire engine power leads to an electricity demand that is likely higher than the power generation capacity of the fuel cell. Hence the battery charge decreases.

The dimensions and characteristics of the fuel cell, battery and engine are, thus, strongly dependent on each-others specificities as well as the physical characteristics of the service area of a bus regarding distances covered, topography and weather. In general, long ascents and descents are more challenging and require more battery capacity than profiles with a continued shift between (moderate) up- and downhill sections. And milder weather conditions are less challenging than strong colds or heat – analogue to the battery electric bus. The chemical reaction in the fuel cell generates heat, which allows for heating the bus in colder weather without considerable need for electricity.

All in all, the traction battery in a hydrogen bus can thus be significantly smaller compared to a battery electric bus, which also results in less energy required during the production of the system components. Compared to conventional bus vehicles, however, also hydrogen fuel cell vehicles require more energy and thus produce more GHG emissions during the production process.

As is the case in the battery electric bus, the electric motor in the hydrogen drivetrain converts 85% of the supplied energy into motion. However, the process of hydrogen production and re-transformation into electricity in the fuel cell comes with a considerable loss of effectiveness: An electrolyser has an efficiency of about 60%; a fuel-cell and battery system in the vehicle has an efficiency of about 55%. The overall primary energy efficiency of a hydrogen bus system based on green hydrogen is therefore only about 26%. That is in the case of green hydrogen produced locally at the bus depot. If hydrogen needs to be transported to the depot from a central production location first, the energy required in this supply chain may further reduce the primary energy efficiency of hydrogen fuel cell bus systems.

Green hydrogen is hydrogen that is produced by electrolysis of water in a CO2-neutral manner. During electrolysis, water is split into its components: oxygen and hydrogen. The electricity required for this is obtained from renewable energy sources only, for example wind power, hydropower or solar energy. Neither the production nor the end products hydrogen and oxygen are harmful to the environment or the climate, making green hydrogen is climate-neutral.

Gray hydrogen is produced by the steam reforming of fossil fuels such as natural gas or coal, in which the waste product CO2 is emitted directly into the atmosphere. For every tonne of hydrogen obtained, ten tons of carbon dioxide are produced at the same time, so that gray hydrogen has a harmful effect on the climate. One also speaks of gray hydrogen if electrolysis of water for the generation of hydrogen makes use of electricity from fossil fuels and non-renewable energy sources and thus not being climate neutral.

Blue hydrogen results from the steam reduction of natural gas. The natural gas is split into hydrogen and CO2. In this steam reforming process, the carbon dioxide is not emitted into the atmosphere, but is stored or further processed industrially. Carbon capture and storage technology (CSS) can be used to store CO2 underground. This means that there are no CO2 emissions whatsoever with blue hydrogen. The long-term consequences of storage are unclear, and leakages can still have negative environmental and climatic influences.

Turquoise hydrogen is produced by a thermal process in which natural gas is split into hydrogen and solid carbon by means of methane pyrolysis. If the carbon remains permanently bound and is not burned during further processing, this process is also CO2-neutral. The reactors used to split the methane should also be operated with renewable energies. In addition, when evaluating turquoise hydrogen, emissions are often also produced when the natural gas is extracted. Turquoise hydrogen is therefore usually not completely climate-neutral.

Hydrogen fuel cell vehicles, like battery electric vehicles, have the advantage of recuperation of energy when breaking or driving downhill. However, in the case of the hydrogen-powered vehicle, the significantly smaller battery size poses a constraint to this recuperation potential: Once the battery is fully charged, any additional energetic potential from breaking or driving downhill is lost, potentially further reducing the primary energy efficiency of the bus system, dependent on the topography of the service area.

Hydrogen buses, like battery electric buses, do not produce any local emissions, with steam water being the only exhaust produced. However, like with electricity generation, not all types of hydrogen are renewable. The differentiation of the various types of hydrogen is based on the varying generation methods and the resulting environmental effect regarding GHG emissions. For vehicles to operate in a truly zero emission fashion, only hydrogen from generation methods that base on renewable energy can be employed.

In Europe, 'green hydrogen' is the preferred choice and considered a significant building block for the continent's energy future due to its relatively positive environmental impact and its potential as a means for using or storing excess energy from wind and solar electricity production.

Hydrogen fuel cell buses have a range of about 400 kilometres and refuelling of a hydrogen bus in normal operation only takes about 15 minutes – for a standard bus demand of about 35kg of hydrogen.

3. Operational models for alternative fuel infrastructure

Due to the component interdependency of vehicle and fuel infrastructure in zero emission bus systems, the development and deployment of the chargers or electrolysers and fuel stations must be considered as integral part of the bus system's design, procurement and operation. The distribution of responsibilities amongst the various players involved in transport production creates three overall scenarios for alternative fuel development infrastructure for public transport.

Bus operator responsible for the alternative fuel infrastructure for its service contract: The contracted bus operator also operates the alternative fuel infrastructure and bares the investment and energy cost risk. This structure has the advantage that it correlates with current tender practices: The transport authority procures a transport service from (or grants a market for transport services to) one operator, that provides the transport capacity and all functions required to produce it. To amortize the incurred additional cost for alternative fuel infrastructure investment, an adjustment of service contracts to the longest possible terms - maximum of 15 years under current rules stated by EU Regulation 1370/2007 - and potentially larger contract volumes compared to current awarding practices appears necessary. Alternatively the residual value risk of the infrastructure would effectively need to be taken from the bus operator. Longer contracting terms reduce planning possibilities and innovative as well as competitive potential for transport authorities. This scenario requires a considerable effort from bus operators both regarding financing capabilities and technical and operational responsibility which may become an obstacle for smaller firms in particular, eventually hampering competition. Incumbent operators may gain a considerable cost advantage compared to new entrants. Various significant risk premiums will likely be priced into the operator's offer.

Transport authority responsible for the alternative fuel infrastructure: 'The transport authority develops and operates the alternative fuel infrastructure, either by itself or by means of an infrastructure tender, and makes it available to its contracted bus operators. The transport authority bares the investment and energy cost risk, providing a save and clear calculation basis and reducing risk premiums associated with the alternative fuel infrastructure being priced into the offers of bus operators. The reduced effort and cost at the side of the transport operators may allow for shorter transport service contract terms and smaller contract volumes, providing an opportunity for smaller, local bus operators and increasing competition. The transport authority can specify the location of the infrastructure and may have an advantage as far as the availability of suitable land is concerned. The organisational and tender-related efforts at the side of the PTA are substantial and require a change in organisational practice for many PTAs. The public responsibility for the infrastructure may allow for synergies if it can be made available for other uses – particularly regarding hydrogen fuel stations and generation facilities.

Third party provider responsible for alternative fuel infrastructure in public access model: The fuelling or charging infrastructure is provided by a third-party infrastructure provider, that bares the investment and energy cost risks. These costs and risks are passed on in the market price of hydrogen or electricity the infrastructure provider charges the bus operator and potential other clients, analogous to today's diesel price. The responsibility for the development of the infrastructure and all related aspects like the availability of land or the creation of a power grid connection of the required size, lay outside of the public transport sector. This means infrastructure locations are not public transport optimized which may result in considerable empty runs of vehicles. Bus operators are The entrepreneurial initiative regarding an enlargement of the infrastructure remains with the infrastructure provider, resulting in a dependency of bus operators, which may lead to risk premiums calculated into a transport service offer.

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