

Review

# On the Historical Development and Future Prospects of Various Types of Electric Mobility

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**Abstract:** Environmental problems such as air pollution and greenhouse gas emissions are caused by almost all transport modes. A potential solution to these problems could be electric mobility. Currently, efforts to increase the use of various types of electric vehicles are under way virtually worldwide. While in recent years a major focus was put on the electrification of passenger cars, electricity has already, for more than hundred years, been successfully used in some public transport modes such as tramways and metros. The core objective of this paper is to analyze the historical developments and the prospects of electric mobility in different transport modes and their potential contribution to the solution of the current environmental problems. With respect to the latter, we analyze the effect of the electricity generation mix on the environmental performance of electric vehicles. In addition, we document major policies implemented to promote various types of e-mobility. Our major conclusions are: (i) The policies implemented will have a major impact on the future development of electric mobility; (ii) The environmental benignity of electric vehicles depends to a large extent on the electricity generation mix.



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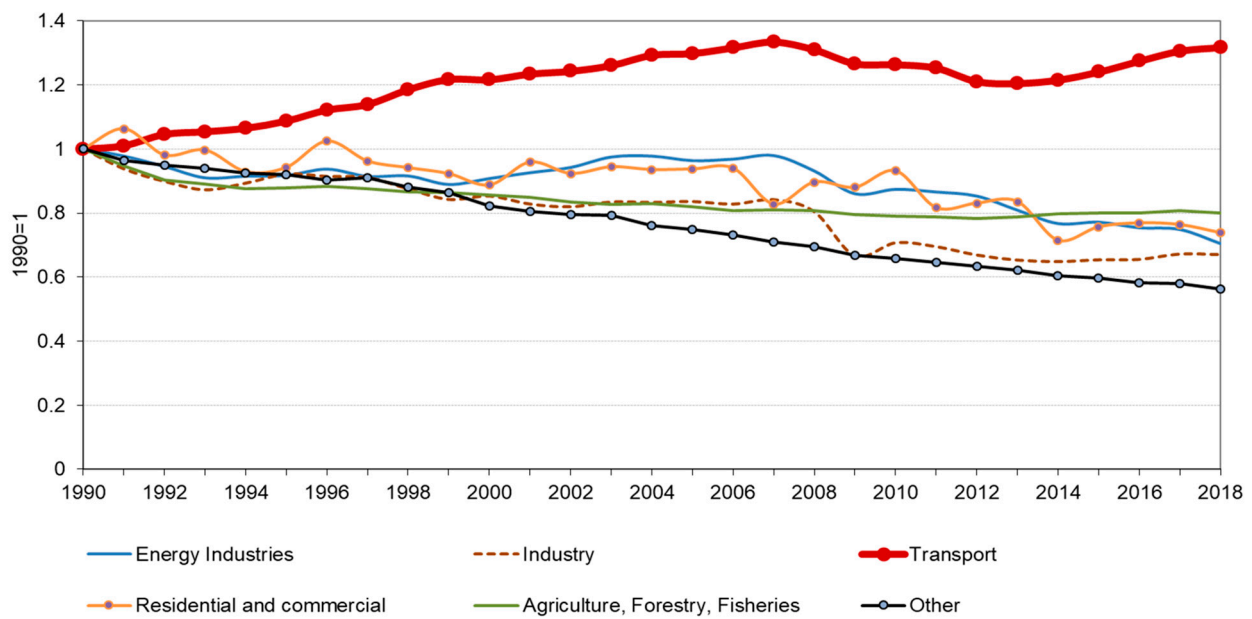


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**Keywords:** electric mobility; environment; policies; public transport; passenger cars

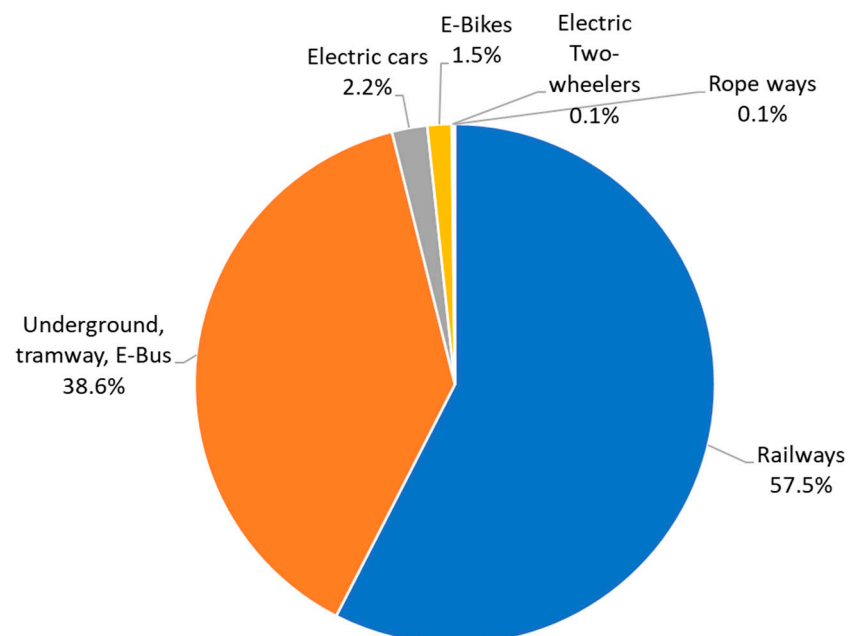
## 1. Introduction

The transformation and electrification of the transport system has become a major strategy in the fight against environmental problems and climate change. In the EU, the transport sector is responsible for a quarter of total greenhouse gas (GHG) emissions. The largest amount of these emissions is caused by road transport, especially passenger cars. In opposition to all other sectors, in which GHG emissions have been decreasing over the last few decades, transport has had by far the worst dynamic performance (see Figure 1). Therefore, electrification of the transportation sector would significantly reduce local air pollution that causes respiratory illnesses and cancer. Moreover, depending on the electricity used, electrification of transport could significantly reduce the amount of greenhouse gases which contribute to global warming. A major challenge today is to identify the proper solutions for the transport sector which can support the transition towards an overall more sustainable energy system. One of the mostly discussed strategies is the “Avoid-Shift-Improve” (The “Avoid” refers to the need to avoid unnecessary travel and reduce trip distances, the “Shift” refers to the need to improve trip efficiency using more sustainable transport modes, and the “Improve” refers to the need to improve transport practices and technologies.) strategy. Although a major focus is currently placed on the electrification of passenger cars, in the future, with the increasing shift to public and shared mobility, it will be important to ensure a high electrification level of almost all transport modes.



**Figure 1.** Development of GHG-emissions in the EU-27 in the different sectors (and transport modes) from 1990–2018 (1990 = 1) (Data source: [1]).

Currently, efforts to increase the use of electricity in the transport sector are underway worldwide. Since many transport modes, such as railways, tramways and metros, are already very well electrified, in the past few years a major focus has been placed on the electrification of road transport, especially passenger cars and buses. Figure 2 shows the example of Austria that the public transport (e.g., railways, underground, tramways and e-buses) contribute to more than 95% of the total kilometers driven with electric vehicles.



**Figure 2.** Shares of different modes and technologies of electric mobility by the number of kilometers driven in Austria in the year 2018 (Data source: [2]).

Although both private and public electric mobility have a long history, they are still seen as a major option for the reduction of the GHG-emissions in the future. Especially in urban areas electric mobility is considered as an important means to solve the local

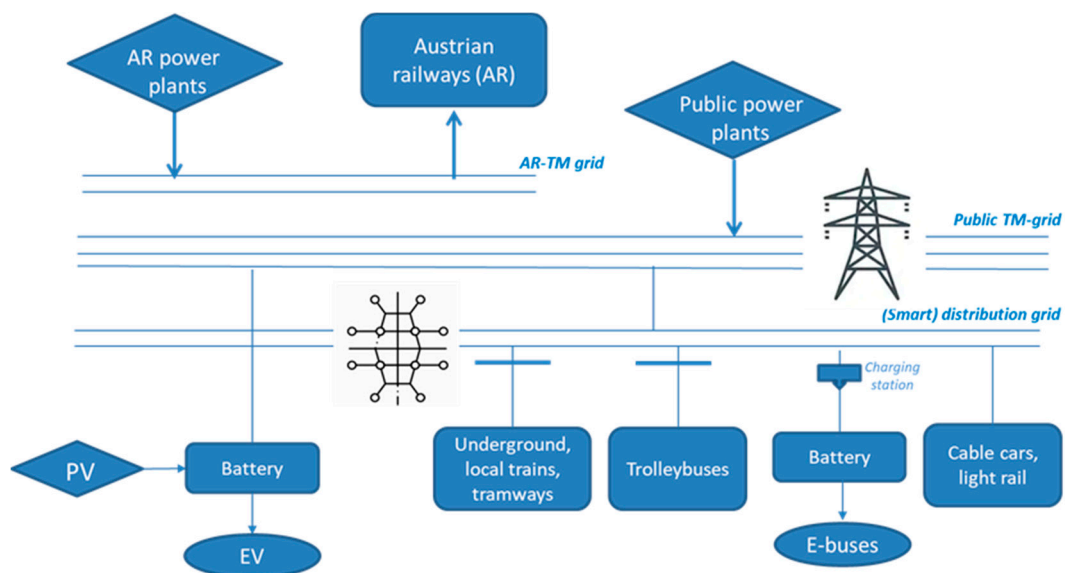
environmental problems. Moreover, the shift from private cars to public transport in combination with electrification is often seen as a major strategy for heading towards sustainable transport systems.

However, surprisingly, in the literature there are only very few contributions analyzing e-mobility in all dimensions and possible applications. Many papers have focused on battery electric vehicles, despite their current minor relevance in comparison to public transport (e.g., trains, railways, underground, etc.), whereas there is a very low number of studies dealing with the electrification of other transport modes.

The core objective of this paper is to document the historical development of electricity use in the transport sector, as well as to analyze the current situation with respect to electric mobility considering all relevant individual and public transport modes. Moreover, the impact of electrification on emission reduction is evaluated in view of different electricity generation portfolios.

To enable beneficial electrification, it is important that the costs of e-mobility are acceptable, that they are competitive with corresponding conventional transport modes, that e-mobility significantly contributes to emission reduction, and that, with increasing use of renewable energy sources (RES), electric vehicles can contribute to better grid management [3].

An example of how different electric transport modes are placed in the electricity system is shown in a stylized description for the case of Austria in Figure 3. The grid issue is of special interest for the electrification of mobility. On the transmission (TM) level, an almost autonomous parallel TM grid exists for Austrian railways (AR). They have their own power plants, mainly from hydro sources. Most other e-mobility applications, such as underground, buses and electric vehicles (EVs), are powered at different levels of the distribution grid. With respect to EVs charged privately, it is important to state that enforcements of network connections as well as of the distribution lines may be required for several applications.



**Figure 3.** A stylized figure of how different modes and technologies of electric mobility are placed in the electricity system in the example of Austria.

This review paper builds on publicly available data sources and all used materials and data are cited in the corresponding sections. They are described with sufficient details to allow others to replicate and build on these results.

It builds on a comprehensive literature review, data collection and documentation by transport modes for private and public mobility, and the environmental assessments are built on methods presented in our previous publications [4,5].

This paper starts with a comprehensive documentation of the historical development of e-mobility in major private and public transport modes. In Section 3, the state of the art in view of e-mobility is presented, indicating the major current challenges. In the following section, a supporting policy framework is discussed. The environmental benefits of e-mobility in relation to the electricity generation mixes are analyzed in Section 5. The major conclusions are derived at the end of the paper.

## 2. History of E-Mobility

Although e-mobility had been very frequently discussed over the last decade, it is important to stress that electricity use for mobility has a long history. Electricity has been used successfully for years in different transport modes such as trams, underground, trolleybuses, and railways.

In this section, we will briefly document the history of electricity use in the transport sector and consider the major private and public transport modes.

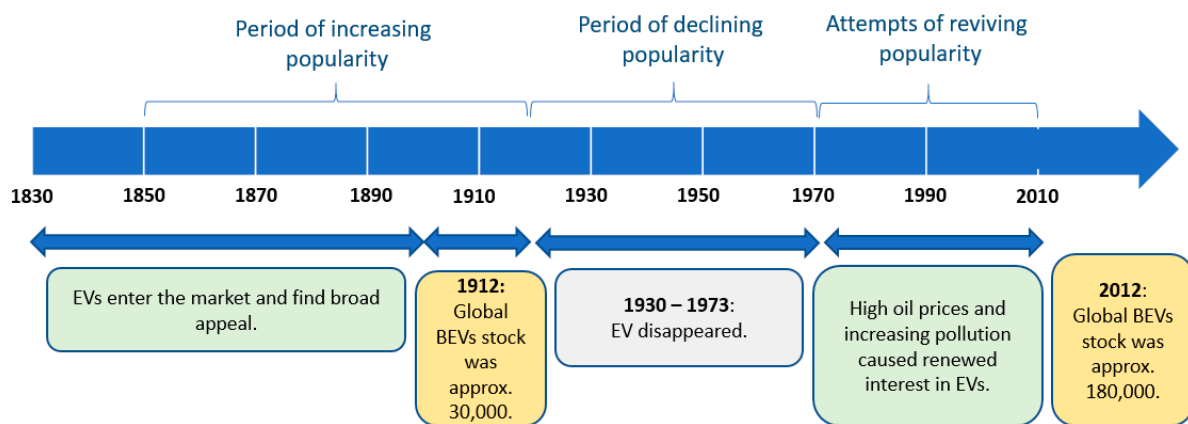
### 2.1. Private Cars

The history of battery electric vehicles (BEVs) is very well documented in different papers and reports (e.g., [6–11]). The fact is that BEVs are not a new automotive technology. They have a long history of about 200 years. About 100 years ago they already played a significant role in passenger car mobility. The history of electric vehicles can be divided into four major segments: (i) 1830s, entering the markets; (ii) from about 1890 to 1920, increasing popularity of EVs; (iii) after 1920, their declining popularity; and (vi) starting in the 1970s, increasing attention [12].

As documented by Høyer (2015) [13], the early history of EVs started with the first tested lightweight electric vehicles constructed in the USA, the United Kingdom and the Netherlands in the 1830s. However, the “first golden age” of EVs was undoubtedly between 1880–1920 in the USA. In 1900, in competition with steam-powered vehicles and gasoline internal combustion engine (ICE) cars, the top-selling cars in the USA were BEVs [14]. Electric vehicles were dominant in the large and developed urban areas such as New York, Boston and Chicago. In these cities the ratio was two electric vehicles to one gasoline ICE vehicle [15].

At that time, there was no clear preference for one of the available automotive technologies, but each technology had some advantages and disadvantages [6]. For example, steam-powered vehicles were cheaper and faster but required a long time to start and frequent water filling stops. The gasoline cars were more dirty, difficult to start and slightly more expensive. However, they were able to manage long travel distances without interruption. The major advantage of BEVs was that they did not have the same disadvantages associated with gasoline cars such as noise, vibrations and smell [16], but they were slow and expensive [6]. Since cars were mostly used in urban areas until the end of the 19th century, due to the low number of the good roads outside cities, the limited driving range of BEVs was not a problem. However, already at the beginning of the 20th century, the need for travel activity increased and car manufactures tried to find ways to make BEVs more suitable for travelling longer distances in the countryside. For example, (i) fast changeable batteries were developed to enable longer driving distances; (ii) regenerative braking systems were introduced, utilizing the capacity of the motor to act as a generator re-charging the battery in the case of driving downhill; (iii) the hybrid vehicle was invented [8,10,13,17]. Although hybrid electric vehicles were able to provide silent mobility with a longer driving range, they were never seriously considered before the early 1970s, mostly due to cost issues [8].

As shown in Figure 4, the first historical peak in EV's global stock was reached in 1912 with about 30,000 cars on the streets [14,18]. However, this peak was followed by a fast decline, which started in the 1920s, mostly due to the beginning of the mass-production of ICE vehicles [16,19], as well as the significant decrease in gasoline prices due to the discovery of new oil fields in Texas.



**Figure 4.** Major milestones in the history of battery electric vehicles.

Such developments, in combination with increasing electricity prices [13,16,19], were the major reasons why BEVs were no longer present in the car markets at the beginning of the 1930s. The renewed interest in EVs started with the first oil crisis in the 1970s, and was intensified with the increasing environmental problems caused by the use of fossil fuels in the transport sector. However, just at the beginning of the 21st century, due to significant technological improvements, electric cars looked more promising than ever before.

Yet, the first attempts to increase the sale of BEVs were not successful, mostly for four reasons: (i) high battery costs; (ii) rather short driving distance; (iii) limited infrastructure; and (iv) a long time to charge the batteries. The current take-up of BEVs is mainly due to supportive policies (see Section 4).

## 2.2. Public Transport

Although a major focus today is placed on the electrification of private cars, the use of electricity in public transport has a long and continuous history. In this section, the historical development of the major public transport modes based on electricity are presented.

### 2.2.1. Electric Railways

The earliest battery electric locomotive powered by galvanic cells was constructed in 1837, Scotland. A few years later a larger electric locomotive named Galvani was constructed, which was first tried out on the Edinburgh and Glasgow Railway in September 1842. However, its limited battery power prevented its general use. This first electric locomotive was demolished by railway workers, because it was seen as a threat to their job security [20,21]. The first practical AC electric locomotive was designed and demonstrated in 1891 [22].

The first electric train for passengers was invented by Werner von Siemens in Berlin in 1879. Currently, the oldest electric railway in the world, which is still in operation, is the Volk's Electric Railway, which opened in Brighton in 1883 [23].

The earliest electrification projects in Europe were focused on mountainous regions to enable easier electricity supply in the regions where hydro power was available. Electric locomotives have been a suitable option on steeper lines.

The first electric mainline railroads were built in the first two decades of the 20th century, in North America, Japan and many European countries. However, since these were often associated with high financial expenses, which was a challenge for the private rail companies, electrification progressed very slowly. Likewise, the accompanying construction of power plants to generate the required electricity was associated with high capital costs. These mostly isolated electrification efforts slowed abruptly or came to a complete stop with the beginning of World War I, especially in Europe. At the beginning of the 20th century, however, the railroad companies started replacing the steam locomotives on some lines due to the many advantages of electric traction.

Figure 5 shows a rough picture of the development of the electrification of railways in selected countries in the period from 1931 to 2019. It can be noticed that in 1930s the level of electrification was very low all over the world. Only Switzerland managed significant progress in this period, and had electrified almost 50% of its network already by 1930.

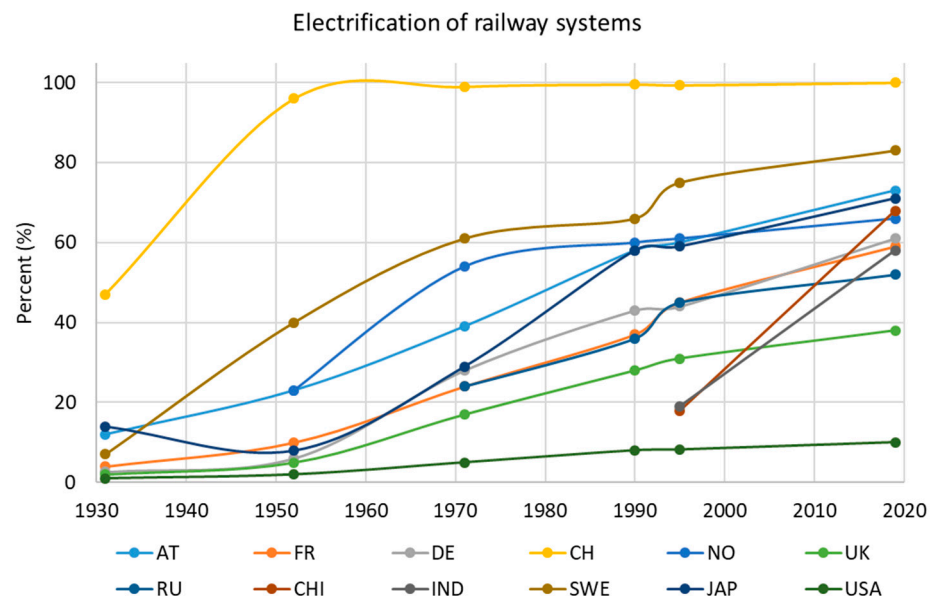


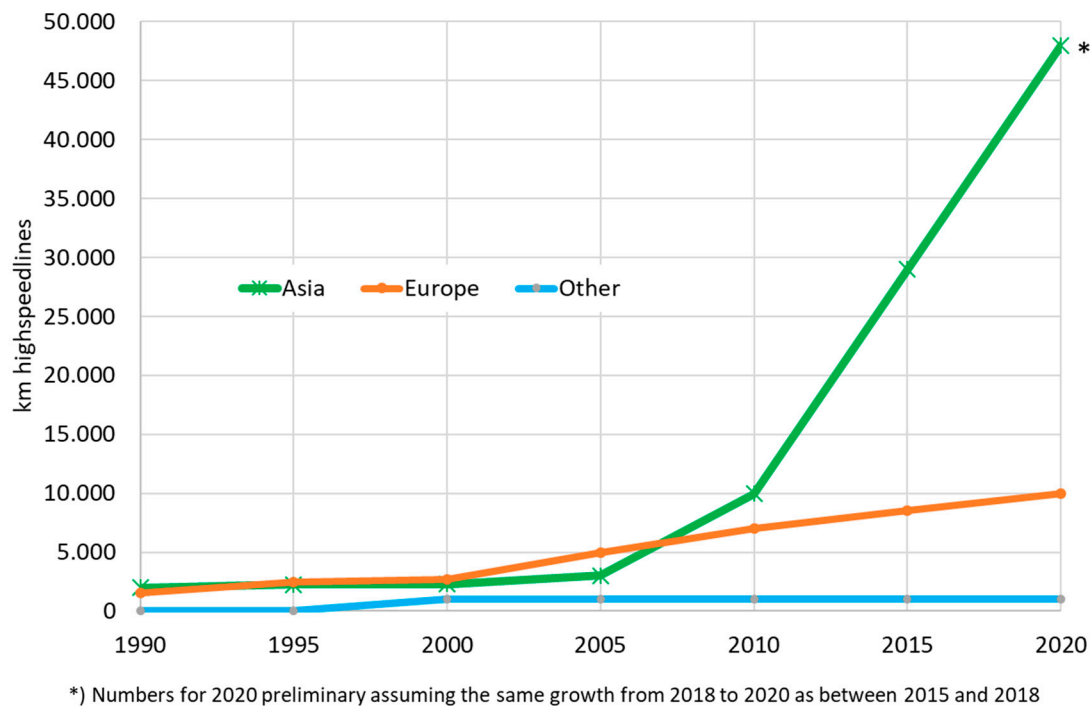
Figure 5. The electrification of railways in several countries, 1930 to 2019.

At the beginning of the Second World War, the expansion of electric railways slowed down again, and priority was given to the production of war materials. Full railway electrification did not take place on a large scale until after the war. As Figure 5 illustrates, countries such as Sweden or Norway, which were exempted from more intensive fighting and bombing, were able to significantly increase the electrification levels of their railway lines. Destruction of infrastructure and lack of capital during the first post-war years resulted in a slow growth and even a decrease of electric lines, especially in Germany and Japan. From the 1950s onwards, an intensive electrification of railway lines took place throughout Europe, as well as in Japan. This development can be clearly seen in Figure 5. However, the increasing degree of individual motorization of the population had a sometimes drastic effect on the railway operators. The consequence was the abandonment of several thousand unprofitable line kilometers. For example, the United Kingdom and France reduced their routes on a large scale. By 1990, the share of electric lines had increased further, partly due to the general conversion to electric operation.

While in Europe, a moderate but continuous growth in electrified lines over the last three decades took place, the growth of Chinese high-speed lines took on an enormous scale from 2008 onwards, mostly due to very high investment [24], and the rapid expansion of its high-speed rail network. In Japan, the electrification of the railways was almost completed before the turn of the millennium.

Of specific interest is the development in the USA. Due to almost private ownership, no costly networks were constructed and, hence, electrification remained very low. In contrast with Europe, in the U.S., railways are mainly used for freight transport. Hence, the corresponding emission of pollutants did not play an important role.

A specific category of electric railways is high-speed trains, with the speeds of at least 250 km/h. The development of high-speed train network lengths over the last three decades in the most important regions worldwide is illustrated in Figure 6.



**Figure 6.** The development of high-speed train network lengths in the period 1990 to 2020 (own analysis, [24]).

After the great success of the TGV in France, many countries, especially in Europe, tried to build their own High-Speed Rail (HSR) lines. In 1992 this was done in Spain and in 1997 in Belgium and Germany, and in the 2000s in Great Britain, Austria, South Korea, Taiwan, China, the Netherlands and other Western European countries. Turkey, Morocco and Saudi Arabia followed in 2017 [24].

### 2.2.2. Tram

Trams are transportation vehicles based on railways. They were originally derived from railway networks towards public urban passenger mobility services. Trams emerged in the first years of the 19th century in South Wales, UK, where a small part of Swansea and Mumbles Railway situated in urban areas was remodeled to be used for trams. However, that very first horse-driven model of the tram does not have many common features with modern tramways [25].

The first electric tram worldwide was invented in 1875 by Fyodor Pirotsky, and the first public electric tramway was put in service in St. Petersburg, but only in September 1880. The first public electric tramway operated in permanent service was opened in Lichterfelde, near Berlin, in 1881. This was the first successful electric tram operated commercially, and it achieved a speed of 24 mile/h and transported 12,000 passengers in its first three months alone [26]. It initially drew its current from the rails, from an overhead wire. The basic principle of that first electric tramway system is still in operation today.

After the first successful demonstrations, electric tramways spread very quickly across European cities at the end of 19th century (see Table 1).

After the successful experiments and implementation of electric tramways in various European cities, they became a common transport mode all around the world.

Electric trams systems in Toronto, Canada were introduced in 1892. In the US, the first commercial installation of an electric tram was in 1884 in Cleveland, Ohio [34].

In Australia the first electric tramway was a Sprague system, firstly shown at the Melbourne Centennial Exhibition in 1888. It was followed by the commercial use of electric tram systems starting from 1889 in many Australian cities (e.g., Adelaide, Sydney, Brisbane, Hobart, Ballarat, Bendigo, Fremantle, Geelong, Kalgoorlie, Launceston, Leonora,

Newcastle, and Perth). However, by the 1970s, only Melbourne remained operating a tram system in Australia [35].

The electric railroad system in Kyoto was the first tram system in Japan, starting the transport of passengers in 1895 [36]. However, by the 1960s, the tram had generally died out in Japan [37,38].

**Table 1.** Some examples of the first electric tramways in Europe [27–33].

Year	Country	City
1887	Hungary	Budapest
1891	Czech Republic	Prague
1892	Ukraine	Kiev
1893	Germany	Dresden
	France	Lyon
	Italy	Milan
	Italy	Genoa
1894	Italy	Rome
	Sweden	Oslo
	Germany	Plauen
	Serbia	Belgrade
1895	United Kingdom	Bristol
	Bosnia and Herzegovina	Sarajevo
1896	Spain	Bilbao
1897	Denmark	Copenhagen
	Austria	Vienna
1898	Italy	Florence
	Italy	Turin
1899	Finland	Helsinki
	Spain	Madrid
	Spain	Barcelona

### 2.2.3. Trolleybus

The trolleybus is an electric vehicle powered by electricity using overhead electrification that first appeared at the beginning of the 20th century in Europe. However, its technological development can be traced back in the early 1880s.

In 1882 Siemens demonstrated the new concept of an EVs powered from a fixed source but was capable of being steered like other road vehicles. This vehicle, called an Electromote, was a light wagonette running without rails, and it was the first trolleybus [39]. The first trolleybus was developed in Germany and put in service in 1901 in Königstein-Bad. The first commercial trolleybus operation in the US was in 1910 in Hollywood. Starting from 1911 the trolleybus was also in use in the United Kingdom [40]. In the early 1920s, there were efforts to establish trolleybus services in many cities. For example, Toronto used four trolleybuses for three years, starting in 1922. On New York's Staten Inlands, 23 vehicles were in operation. However, most of these buses were in operation for just a few years [40]. These early vehicles were not particularly elegant. In contrast to the tram, which was very fast established as the major urban public transport mode, the trolleybus remained in a primitive state until the mid-1920s. Just throughout the 1930s, with improved technology, trolleybuses gained attention for reliability, speed and comfort. For example, by 1939, there were 35 trolleybus systems in operation in London involving 3429 vehicles [39]. Furthermore, in the USA, trolleybuses were widely accepted as important city transportation services. For example, in 1927, 12 trolleybuses were running in New York and in 1929 26 vehicles were in service in Salt Lake City. The largest trolleybus system with 300 trolleybuses was installed in Seattle before the Second World War.

During the war, independence of imported fossil fuels was a huge advantage for electric vehicles, including tram and trolleybuses; however, in this period their infrastructure was gravely damaged in most European urban areas. After the war, due to the development of large diesel buses, as well as increasing growth of the urban population,



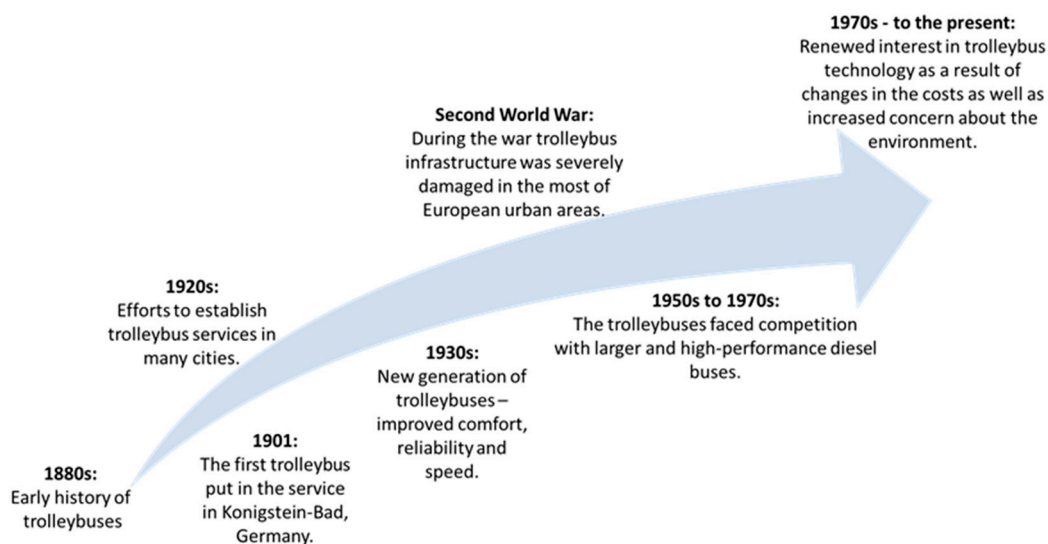
more flexible diesel buses appeared to be a better option for mobility in many cities. For example, in 1954, London declared its plan to replace all its trolleybuses with diesel buses, and the last trolleybus system in the UK was closed in 1972. A similar pattern was also seen in other countries. However, especially in South-Eastern Europe, e.g., in Sarajevo, trolleybuses still provide a significant contribution to public transport.

Although trolleybuses have certain advantages, such as their quietness, their vibration-free operation, their long lifetimes and low maintenance requirements, as well as their absence of local pollution, they have been ignored in many countries which have discontinued trolleybus operation due to their disadvantages, such as their operational inflexibility and costs. The trolleybus and overhead lines were expensive and energy costs were also relatively high. The cost of operating trolleybuses was becoming significantly greater than that of motor buses in the same service. The availability of mass-produced diesel buses led to a gradual decline and, in some cases, total abandonment of trolleybuses. For example, in England all trolleybus systems were abandoned by 1972. In Germany, which at one time had 50 operating trolleybuses, only six remained by 1977 [40]. Mostly Eastern European countries continued with trolleybus operations.

However, just few years after trolleybuses were banned in most cities, oil crisis and increasing petrol prices made them attractive again for some countries. The renewed interest in trolleybuses started in the early 1970s as a result of changes in the costs, as well as increased concern for the environment, and this continues to the present. In Europe, interest in the electrification of mobility, including different demonstration programs, started at the beginning of 1970s, mostly due to supporting measures provided by governments and public authorities. At that time, commercial vehicles were considered to be more suitable for the early diffusion of electric vehicles.

Some countries re-equipped existing trolleybus systems (e.g., France, The Netherlands, the USA), and some opened a new system (e.g., Belgium, South America). However, this revival of the trolleybus was moderate due to the expansion of light rapid transit and underground systems worldwide. Yet, trams, underground systems, light rapid transit and trolleybuses have a lot of joint characteristics. They are quiet, powered by electricity and are locally pollution-free.

The major milestones in the development of trolleybuses are depicted in Figure 7.



**Figure 7.** The major milestones in the development of trolleybuses.

#### 2.2.4. Underground

The first underground railway system worldwide was constructed in London. It was originally opened in 1863 for steam-powered locomotive trains, and in 1890 it was the

world's first electrified underground network [41,42]. Three years later an electric railway in Liverpool was opened. On the continent, Budapest opened the first electrified underground line in 1896. The first line of the Paris Metro opened in 1900. The Berlin "U-Bahn" opened in 1902. Since many sections of the line were elevated, it was also called "Hochbahn" (high railway). Germany's next U-Bahn was opened in Hamburg in 1904. In Vienna, an old two-line Metropolitan Railway, which was in operation since 1898, was transformed to a modern underground railway system in 1978.

New York City built its first rapid transit line in 1868, and the first section of 14.5 km of the New York subway opened in 1904 [42].

In 1913, in Buenos Aires, the first subway in the Southern Hemisphere opened as an underground tramway [41].

In Japan the first subway line opened in 1927 in Tokyo. During a time in which steam engine locomotives were the widest-used type of locomotives, the Tokyo metro started the development of the 1000 Series electric train for the use underground [43].

The construction of the Moscow metro started in 1931 and already in 1935, the first stations were opened to the citizens. This first metro line had a length of 11 km [44,45].

The first discussions about the Beijing metro system started in the early 1950s when the Chinese capital had about 5000 vehicles and a population of about three million. The then-premier, Zhou Enlai, said, "Beijing is building the subway purely for defense reasons. If it was for transport, purchasing 200 buses would solve the problem." [45,46]. Yet, Beijing's subway, which opened in 1971, is currently one of the most frequented in the world, transporting approximately 10 million passengers per day. In 2002 the system began its rapid expansion. However, the existing grid is still not able to adequately meet Beijing's mass transit demand.

### 3. E-Mobility: State of the Art

In the past, the use of electricity in the transport sector was mostly focused on public transport. However, increasing emissions, especially from the road transport, have changed the priorities over the last few decades. Currently, major effort has been put into the electrification of road transport, especially passenger cars. With the decrease in battery prices, as well as significant technical improvements, interest in the electrification of almost all transport modes is rapidly increasing.

#### 3.1. Road Transport

Road transport is currently on the frontline of electrification, especially passenger cars and city buses.

##### 3.1.1. Passenger Cars

Road transport, especially light duty vehicles, cause the largest amount of transport emissions. The electrification of road transport is seen as an essential strategy for meeting the European emission reduction goals. Electrification of transport combines the advantages of more energy-efficient automotive technologies with an increasing replacement of fossil fuels by renewable energy sources. However, electrification will not just change the powertrains used, but also the conditions of its use, leading to new user behavior and preferences.

Because of this complexity, the number of BEVs on the road is still very low but is continuously increasing, mostly due to the different kinds of supporting policy measures implemented as well as the increasing installation of public charging infrastructure.

In 2010, just about 17,000 electric cars were driven worldwide. However, there were just a few countries with more than 1000 electric vehicles: China, Japan, Norway, UK and USA. The majority of electric cars were used in the scope of different pilot and demonstration projects, and they were largely supported by governments through various incentive schemes and tax waivers. In 2010, the ratio of consumer spending on EVs and government spending was about 60% to 40%. In the meantime, acceptance of EVs has significantly

increased, so that the ratio of consumer spending on EVs is more than 85%. The drop in government spending is mostly due to changes in incentive schemes in the US and China [47].

In spite of this, there were about 7.2 million electric cars in 2019 worldwide, and the leading countries/regions in the electrification of passenger vehicles were China, Europe and the United States. Almost half (47%) of the world's EVs stock was in China, 25% in Europe and 20% in the United States.

Figure 8 shows the development of the global stock of rechargeable electric vehicles. Battery electric vehicles accounted for the majority (67%) of the world's EVs in 2019.

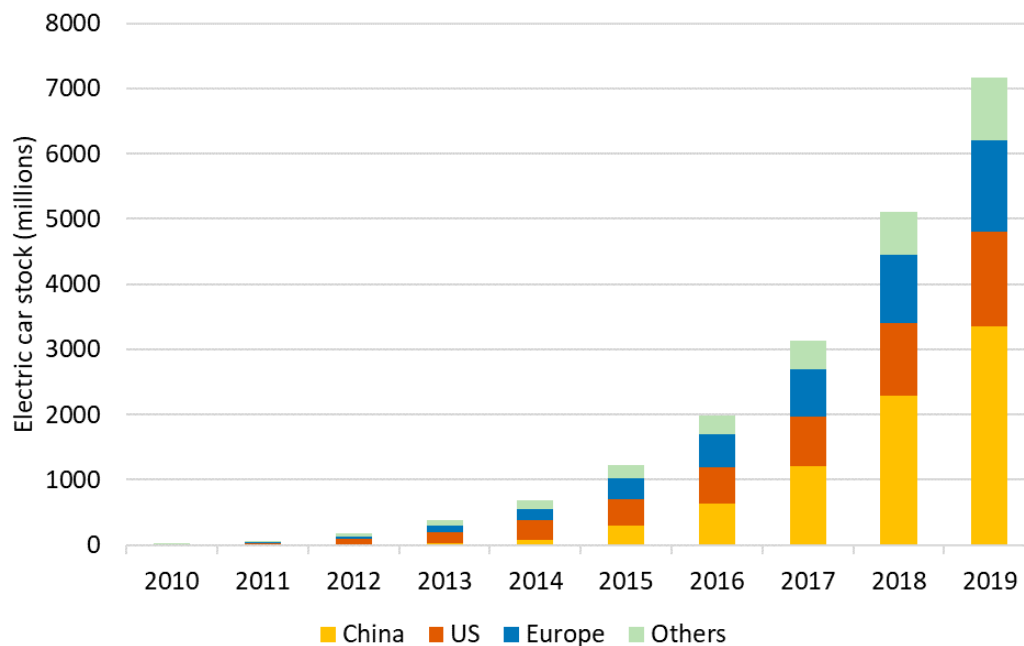


Figure 8. The global stock of rechargeable EVs, 2010–2019 (Data source: [47]).

However, based on the share of EVs in the total vehicle stock, Norway is the worldwide leader. For example, the electric car market share in Norway was 56% in 2019, followed by The Netherlands (15%) and Sweden (12%). In most other countries, the electric car market share is well below 5% [47].

Although 25% of the global stock of EVs is in Europe, the penetration of BEVs on the EU market is relatively slow. In spite of the low numbers and market shares (just about 2 % of new registered passenger cars), new BEVs registrations in the EU have been continuously rising in recent years [47].

### 3.1.2. Electro Micro-Mobility

Interest in electro micro-mobility (e.g., e-scooters, e-bikes) has been rapidly increasing since their emergence in 2017 [47]. They are especially of interest in urban areas and for shared mobility. Since in most of the countries/regions (e.g., China, the EU, USA) about a half of passenger-kilometers are short trips of under 8 km, there is huge potential for electro micro-mobility [48]. Such mobility can lower local air pollution and noise in cities. Yet, their full environmental impact is dependent on their total life-cycle emissions, which are determined mostly by the carbon intensity of electricity used, as well as embodied emissions. The impact of embodied emissions is very dependent on the lifetime of the electro micro-mobility. Moreover, there is an important question: which modes are replaced by micro-mobility, e.g., public transport or private cars. For example, in most cases, e-bikes are just replacing normal bicycles.

However, besides personal mobility, some of the electric micro-mobility vehicles can play an important role in last-mile delivery in urban areas. E-cargo bikes are already being used in several European cities for different delivery and courier services.

### 3.1.3. Two-Wheeled Electric Vehicles

Electrification of the two-wheeled vehicles has been intensified over the last few years, especially in Asia. The low weight and energetic need of two-wheelers make them suitable for electrification. They are of special interest for use in urban areas for short distances.

Currently, China is the leader in the two-wheeled electric vehicle market, with about 300 million units on the roads [47]. Major reasons for high deployment of two-wheeled vehicles in China are regulations and modest prices. For example, electric two-wheelers are exempted from registration taxes and are allowed to be used in bicycle lanes. Moreover, several cities have banned fossil fuel powered two-wheelers from downtown areas [49].

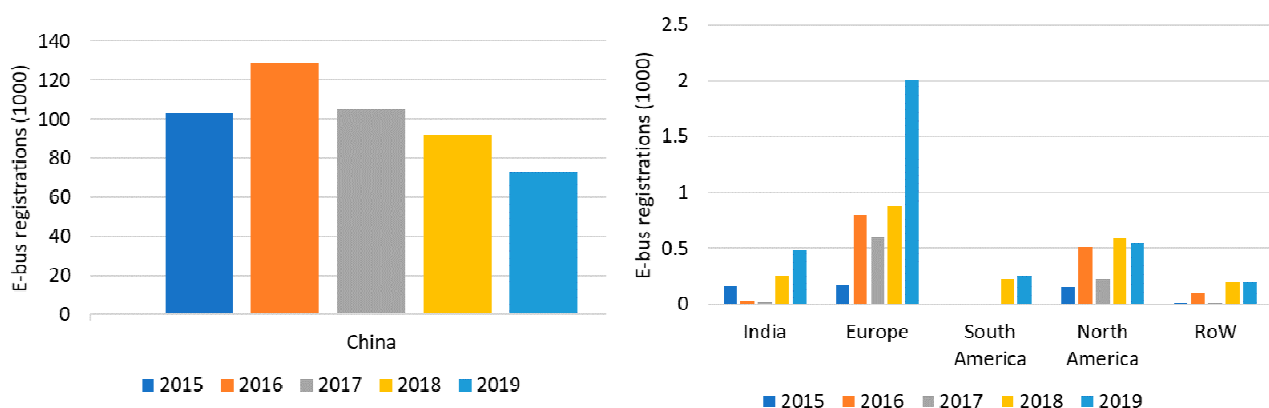
However, in other Asian countries, which use nearly 900 million two-wheeled vehicles, electrification is still marginal. Although about 20% of CO<sub>2</sub> emissions and 30% of particulate emissions in India are caused by motorized two-wheelers [50], India has just about 0.6 million electric two-wheelers [51]. The sales of electric two-wheelers increased from 54,800 units in 2018 to 126,000 units in 2019; however, this is still very low number compared to the total two-wheeler sale which reached a record of 21 million units in 2019 [47,52].

In Europe and the United States, electric two-wheelers are in competition with electric bikes, which do not require a driver's license or insurance [53]. Still, an increased use of shared electric two-wheelers can be noticed in Europe.

### 3.1.4. Electro Buses

Urban buses are the first road transport mode where electrification over the last few years is already having a significant impact [54].

The number of electric buses is growing all over the world. However, roughly 98% of electric buses are currently deployed in Chinese urban areas. Already in 2016, China registered on average 340 electric city buses per day. At the same time, in Europe about 70 new buses were put on the road, including all bus categories (e.g., urban, intercity, coaches) and all fuel types. Europe and United States, as well as other countries, still have a minor role to play in the adoption of electric buses. The new electric bus registrations in China and other countries/regions are shown in Figure 9.



**Figure 9.** New e-bus registrations by country/region, 2015–2019 (Data source: [47]).

Although the number of E-bus registrations in China has been decreasing over the last few years, mostly due to the reduction of subsidies, the numbers in all other countries are negligible in comparison to China.

Worldwide, there were about 513,000 electric buses in 2019, see Figure 10. The majority of them, about 95%, were made and sold in China [47]. In China the share of e-buses in the total municipal bus fleet is about 18% [55]. The Chinese electrification plans for public

transport are pretty ambitious. A good example is the city of Shenzhen in which all ICE buses have been replaced with electro buses (about 16,500 buses) [55].

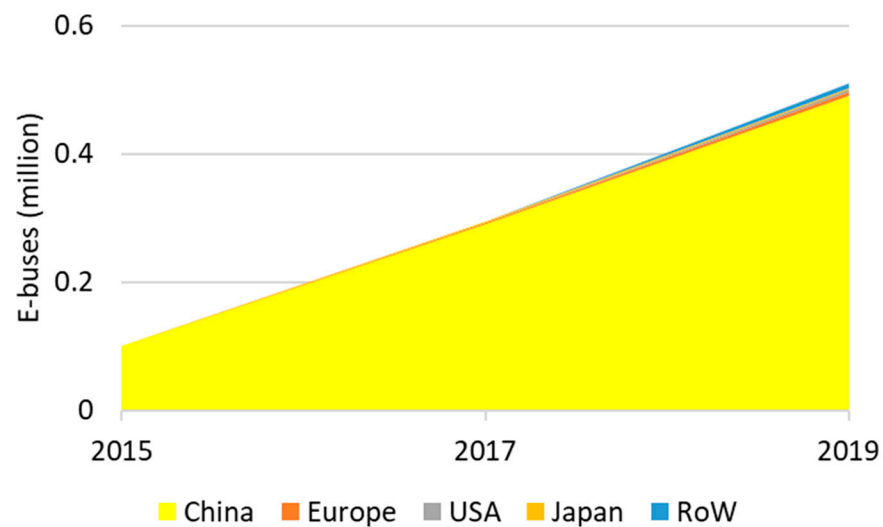


Figure 10. Development of the global stock of E-buses (Data source: [56]).

Over the last few years in Europe the number of e-buses has remarkably increased. In 2019, Europe registered 1900 electric buses [47]. The percentage of e-buses in overall city bus sales was about 10%. According to ACEA, 4% of new bus registrations in 2019 were e-buses [57]. The majority of electric buses in Europe is used in four countries: the UK (800), the Netherlands (800), France (600) and Germany (450) [47]. The Netherlands and the UK are leading European countries in electric bus adoption.

In 2019, the North America's electric bus fleet consisted of 2255 e-buses, of which about 500 were new registrations [58]. Furthermore, India and South America are markets with big potential in bus electrification [47,59] (see Figure 9).

Despite the high efficiency of e-buses and their low maintenance costs, their high purchase price is a significant obstacle for faster market penetration. The share of the purchase costs in the total costs of ownership (TCO) of e-buses is about two times higher than in the case of diesel buses (see Figure 11).

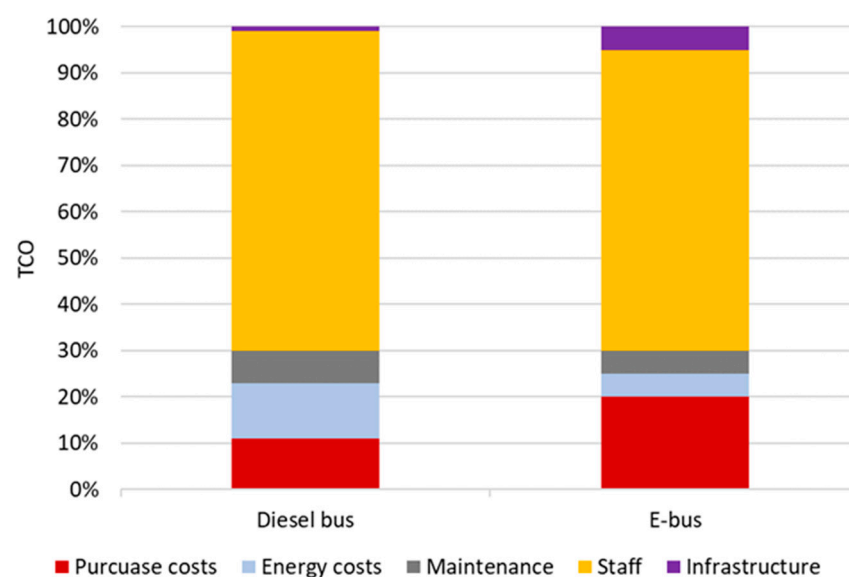


Figure 11. TCO for diesel and e-buses (Data source: [55], own analysis).

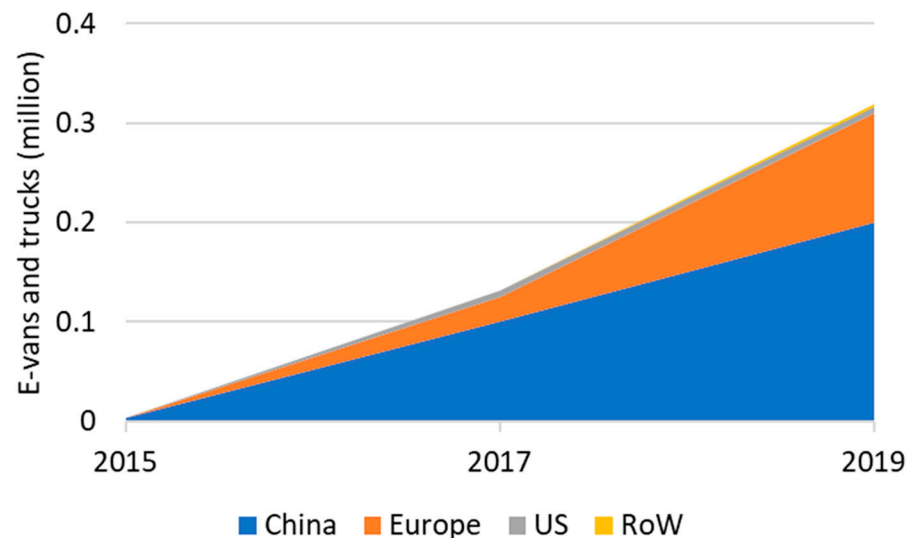
However, total energy consumption can increase by 50% due to the use of e-bus climate systems, leading to a substantial reduction in the driving range.

In any case, use of e-buses in urban areas can significantly reduce local air pollution, but full environmental benefits are very dependent on emissions related to electricity generation mix, as well as manufacturing and recycling of batteries.

### 3.1.5. Electric Trucks

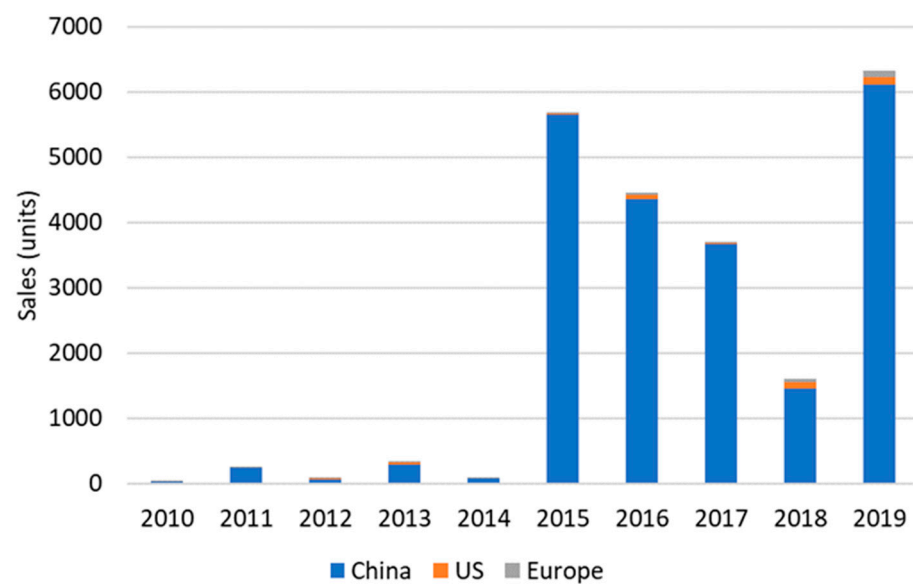
Currently, electric trucks are mostly used in niche markets and in the scope of different pilot and demonstration projects. The battery pack with its very low volumetric energy density is the major impediment of a wider dissemination of electric trucks. The energy density limits driving range and load capacity. However, when driving on an uncongested highway, e-trucks can reach powertrain-to-wheel efficiencies of about 85%, while a conventional truck can achieve efficiencies of no higher than 30%. Currently, most e-trucks operate in urban areas in the scope of different municipality operations, such as delivery or garbage collection [60].

The deployment of e-vans and e-trucks is shown in Figure 12. It is obvious that China has predominance in this vehicle segment too.



**Figure 12.** Development of electric vans and trucks, 2015–2019 (Data source: [56]).

In 2019 more than 6000 medium- and heavy-duty electric trucks were sold in China, mostly due to government subsidies but also due to improvements in battery performance, their cost reductions, as well as the increasing number of truck models. Currently, the most-used type of battery in trucks is lithium-ion chemistries [61]. However, in Europe and the USA, medium- and heavy-duty electric trucks are still largely used just in demonstration projects. Figure 13 shows the numbers of medium- and heavy-duty e-trucks sold worldwide in the period 2010–2019.



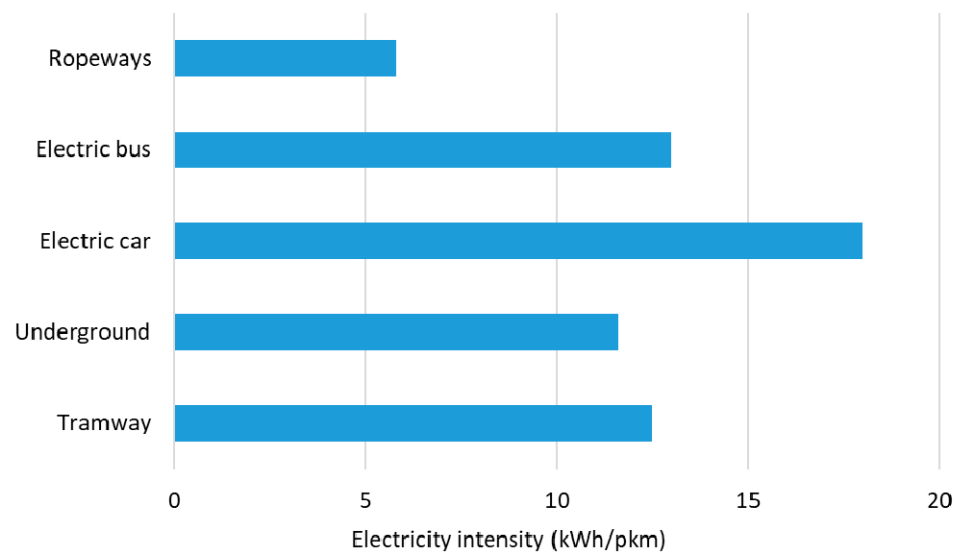
**Figure 13.** Global sales of e-trucks (Data source: [47]).

### 3.1.6. Ropeway Transport System

The ropeways have so far mainly gained attention in mountain areas for tourist purposes. The first ropeways were constructed about 100 years ago in the Alps, in Switzerland and Austria. However, in recent years they are becoming a novel option in urban public transport. Ropeways are spreading practically all over the world. Residents of Medellín in Colombia, for example, have been using cable cars to get to work since 2004. In the Turkish capital Ankara, the largest urban ropeway project on the Eurasian continent was realized in 2014. At a height of 60 m, residents of the suburbs use it to float into the city center. The largest ropeway grid in an urban area has been in the Bolivian capital La Paz since 2014. It stretches 33 km, linking the city center to the densely built-up poor neighborhoods. It comprises ten ropeway lines with hundreds of gondolas transporting around 300,000 passengers a day [62].

In regions with a hilly topography, electric ropeways could be a good alternative to buses and trains. Since electric ropeways are generally considered an environmentally benign technology with a small ecological footprint, their popularity is increasing worldwide, particularly in developing and emerging countries.

However, as with every other technology, they have some advantages and disadvantages. Besides their low environmental footprint, they have a high capacity of up to 5000 people per hour and direction. To achieve such transport performance on the road, double-articulated buses would have to run every two minutes. Ropeways are also technically mature systems and are statistically among the safest means of transport in the world [63]. Unlike buses, they also overcome steep gradients and do not get in the way of traffic lights or other vehicles, and thus avoid traffic jams. Among the biggest advantages are their low cost and short construction times, ideally only a few months. Moreover, ropeways have a high energy efficiency. According to surveys commissioned by the German Federal Environment Agency, ropeways consume 5.8 kWh per 100 passenger kilometers—only half of the already quite efficient underground, and they are clearly favorable in comparison to electric buses or individual BEVs (see Figure 14).



**Figure 14.** Electricity intensity of various modes of e-mobility in cities (Data source: [64], own analysis).

Nevertheless, there are some technical limits. The rope drive is only suitable for stretches of about five kilometers in length. With several sections, distances of any length could be covered, but then another disadvantage would come into play: ropeways can hardly manage more than 25 km per hour in circulating operation [65]. At higher speeds, boarding and alighting would no longer be manageable.

### 3.2. Other Transport Modes

Currently major focus is placed on the electrification of road mobility, especially passenger cars. However, there are many activities also in the electrification of other transport modes.

Although not very frequently discussed, rail transport is the major electrified transport mode today. In Europe, about 60% of the railway grid is already electrified and about 80% of rail transport is running on these lines. Furthermore, almost no technical obstacles for further electrification exist. However, further electrification of the rail transport is dependent on a cost–benefits ratio. For example, there is no interest in replacing diesel trains with electric ones on the low-density lines. Considering the costs for electrification of rail infrastructure and the expected emission savings, the best solution is the electrification of busy lines.

In contrast to the problem-free electrification of rail transport, electrification of shipping and aviation is still a big challenge.

After a number of pilot projects of small battery electric aircraft flights over rather short distances, the first commercial passenger aircraft flight of a full electrified airplane took place in December 2019; however, this was just for 15 min. The major problem for the electrification of aviation is the relatively low battery energy density. In spite of the fact that a growing number of aviation companies is developing small electric planes, mostly for test and demonstration purposes, the electrification of the aviation sector is still in its very early stages [47].

Electric ship propulsion actually has a long history, reaching back more than 100 years; however, this is in very limited numbers [66,67]. What are usually considered the first generation electric propulsion ships are those built in the 1920s, although there are also earlier examples of diesel-electric propulsion ships, e.g., the river tanker Vandal launched in 1903 [68]. An example from 1935 is the passenger liner “S/S Normandie” with  $4 \times 29$  MW synchronous electric motors, one on each of the four propeller shafts. However, until the 1980s electric propulsion was not used very often, but with the rapid development of high-power semiconductor switching devices, interest in electric ship propulsion rose again.



Currently, the electrification of shipping is making progress, yet it is still very limited due to the required ranges and battery performances. At present electricity is used just in some ferries and short-distance vessels. Norway is a worldwide leader in electrification of mobility, with about 20 electric ferries in use. However, also other countries, such as China, Finland, Denmark, the Netherlands and Sweden are starting with the use of electric ships. For river navigation and short distance maritime transport, electrification could bring significant benefits in improvement of air quality. However, the major challenge is cost competitiveness.

#### 4. Policies

As in many other sectors of an economy also in transport private initiatives do not always bring about the optimal solution for society, e.g., due to market distortions or neglect of environmental externalities, such as local air pollution or global GHG emissions. In such cases, local or federal governments usually interfere to correct for these failures and support the change in the “right” direction. The major instruments to do so are regulations, taxes, subsidies and standards [69–71]. In the following, we discuss the major policy interferences regarding the progress of electrification of public and private mobility.

In the beginning of the 20th century in most USA- and European cities it was full competitiveness in the private and public passenger transport [6,13]. No subsidies for any specific vehicle type (e.g., steam, electric, petrol, etc.) were provided, no specific taxes were charged and no standards were implemented.

After this first phase, private electrification efforts virtually died out. What followed were the initiatives for electrifying national railway systems by federal governments, as well as electrification of the public transport (e.g., trams, underground trains and trolleybuses) by the municipalities of cities [72]. However, these efforts were quite different from country to country and policy framework played an important role. One of the major issues in this context is the ownership structure. Indeed, as with the provision of infrastructure in the electricity system itself, but also with respect to public transport, the infrastructure for electricity, e.g., the overhead lines, which are a major cost factor, depended on the ownership structure. For example, in the USA, where the railway companies are privately owned, up to today only a very moderate electrification has taken place [73].

Over the last decade, electrification of mobility was driven by ambitious targets and policies set with the goal to reduce fossil fuel use in the transport sector, as well as to reduce local and global environmental problems [74–76]. Worldwide, governments have introduced a broad portfolio of policies which should enable a more sustainable development of the transport sector including all transport modes. Mostly, used policy instruments are national GHG reduction targets, fuel efficiency targets, CO<sub>2</sub> emissions standards, vehicle sale targets/mandated, and different kinds of supporting monetary measures (e.g., incentives, subsidies, tax exemptions or reduction, etc.) [69,70] Moreover, there is a broad portfolio of non-monetary measures such as free parking areas for EVs, possibility for EV drivers to drive on bus lanes, avoidance for EVs to drive in city centers as well as zero emission zones [77].

Besides these direct measures implemented to accelerate the uptake of EVs, diesel-emission scandals and announced bans of ICE vehicles are indirectly supporting the electrification of mobility. For example, it is announced that all new cars and vans sold in Norway should be zero-emission vehicles starting from 2025. The same goal has also been announced by other countries, starting, however, from 2030 or 2040 [47]. Moreover, European mandatory CO<sub>2</sub> emission target for the new passenger cars—95 gCO<sub>2</sub>/km in 202—should initiate the production and dissemination of more green automotive powertrains with, in the ideal case, nearly zero emissions. Currently, very ambitious targets and more severe emission testing procedures are set for the years 2025 and 2030 [78]. For the achievement of these targets, the increasing use of more environmentally benign vehicles such as BEVs is essential.

There is a broad portfolio of the policy instruments used for the promotion and support of EVs. However, as discussed in the literature [79–81], measures and policies related to the purchase of EVs (e.g., tax exemptions, subsidies) are considered to be the financial instruments with the highest effectiveness, especially in countries with high registration tax rates for conventional vehicles, like Norway or the Netherlands. As discussed by Ajanovic et al. [79], consumers usually do not consider total costs of car ownership, so that benefits during the operation of the cars, such as lower or zero annual circulation taxes, often provide only a small price signal and finally, have less of an impact on ordering an electric vehicle [82].

Currently, the range of subsidies for the purchase of a BEV is between 4000 and 6000 EUR [47]. Since in most of countries these subsidies are very important and their use is increasing over time, China, as a leader in the electrification of road transport, is already in a position to reduce direct subsidies. The policy framework for EVs in China is in transition from direct to more indirect supporting measures, including the development of the charging infrastructure.

Although the USA has a long history in promotion of energy efficient vehicles, starting with the Corporate Average Fuel Economy Standards in the 1970s, they have only a 20% share in the global stock of the rechargeable EVs. With the proposed vehicle fuel-efficiency standards in 2020, the annual improvement in fuel-economy standards should be reduced from 4.7% to 1.5% for model years 2021 through to 2026. Moreover, it was decided to not extend the federal tax credit for the purchase of electric vehicles [47]. However, California is a leader in the adoption of ambitious policies for the promotion of zero-emission medium- and heavy-duty vehicles.

In the EU, many policy goals are focused on the reduction of GHG emissions and an increase of RES in electricity generation, as well as in the transport sector. Almost all policies implemented and targets set support the use of EVs, directly or indirectly, for example, EU CO<sub>2</sub> emissions regulations (no. 333/2014) [83], the European climate and energy package [75,76], the White Paper on Transport [84], the European Green Deal [85]. Besides policies and goals at the EU level, almost all EU countries have a wide range of supporting policies for the promotion of EVs implemented on the national and local level.

## 5. Environmental Issues of Electricity

One of the most important reasons to increase the use of e-mobility is to reduce the local and global emissions. However, whether this effect will be reached in practice and to what extent depends almost solely on the primary energy mix used in local or national power plants for electricity generation. The environmental benignity of electric vehicles in relation to the electricity mix used is comprehensively analyzed in the literature [86–89]. Nordelöf et al. (2014) [86] provide a review article investigating the usefulness of various types of lifecycle assessment (LCA) studies of electrified vehicles. Van Mierlo et al. (2017) [87] analyze the impact of the electricity production on the overall LCA performance of EVs and how the energy source mix for electricity generation influences the impact. Moro/Helmerts (2017) [88] conduct an analysis on the advantages and drawbacks of the Well-to-Wheel (WTW) methodology when compared with the life cycle approach based on the EU electricity generation mix. In the recent publication, Ajanovic et al. (2021) [89] provide assessment of CO<sub>2</sub> emissions of various transport modes for the case study of Vienna.

In practice, a broad range of primary energy sources is available for electricity generation and there is a significant difference in electricity generation mixes across the countries. Figure 15 shows the mix of inputs for electricity production in selected countries/regions. While in China the electricity mix is dominated by coal, about 70%, in Japan and the US the share of coal is much lower, and the largest share has natural gas leading to a lower specific emission. In Europe, due to the continuously increasing use of RES, total share of fossil energy in the electricity generation mix is about 40%. However, there are significant differences across European countries. An exceptional country is Norway, with very high uses of RES, almost solely hydro, for electricity generation.

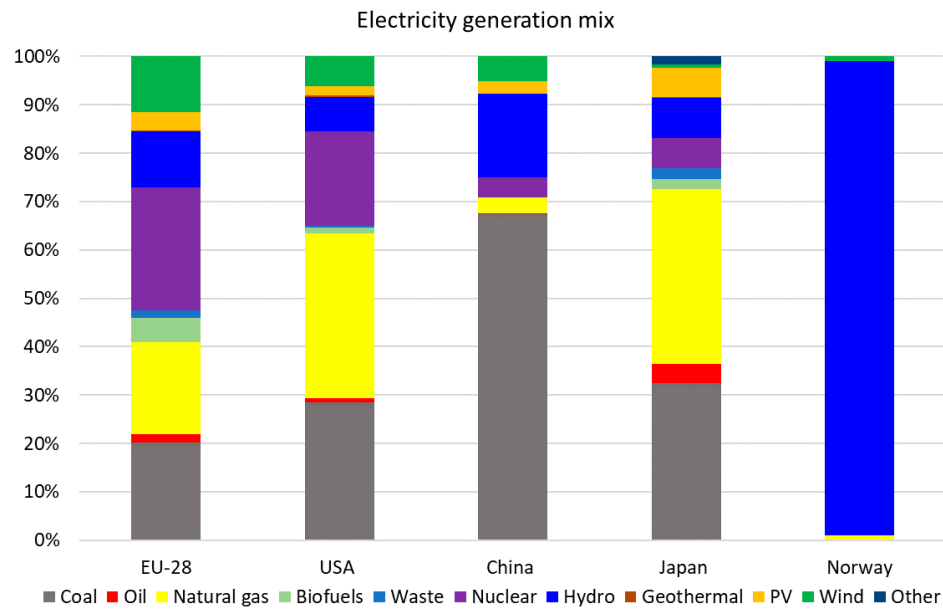


Figure 15. Electricity generation mix in selected countries 2018 (Data source: [90], own analysis).

The portfolio of energy inputs for electricity generation is changeable over time, as well as the corresponding carbon intensity of the electricity mix, see Figure 16. This figure depicts the development of specific CO<sub>2</sub> emissions of electricity generated in various countries from 2000 to 2018. As can be seen, the specific emissions have decreased in all regions shown since 2000 by almost the same percentage. The IEA expects almost continuous further decreases up to 2040 [91]. An exemption is Norway, where almost 100% of electricity is generated in hydro power plants and a further decrease of CO<sub>2</sub> emissions of electricity is virtually not possible.

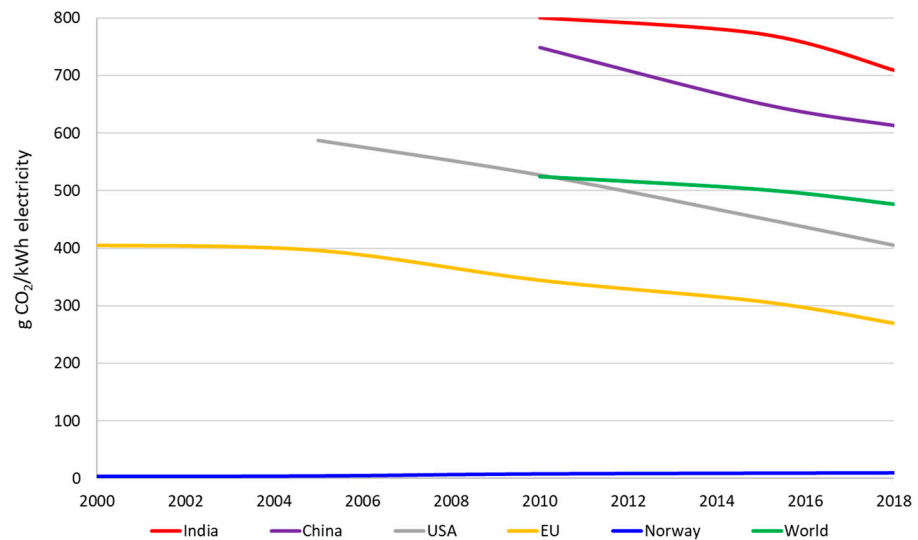
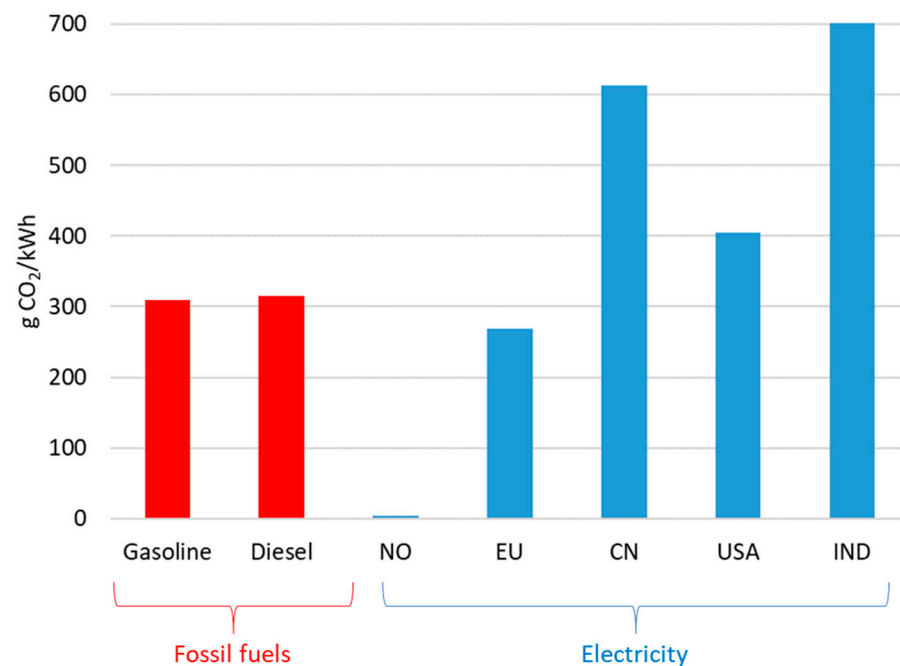


Figure 16. Development of specific CO<sub>2</sub> emissions of electricity generated in various countries and world-wide 2000–2018 [91,92].

A comparison of specific CO<sub>2</sub> emissions of electricity generated in various countries compared to gasoline and diesel is illustrated in Figure 17. This figure shows that related to kWhs, CO<sub>2</sub> emissions are higher for electricity.



**Figure 17.** Specific CO<sub>2</sub> emissions of electricity generated in various countries compared to gasoline and diesel.

As can be seen, in some of the countries with a high use of coal in electricity generation (e.g., China and India), a specific carbon intensity of electricity mix is much higher than those of gasoline and diesel.

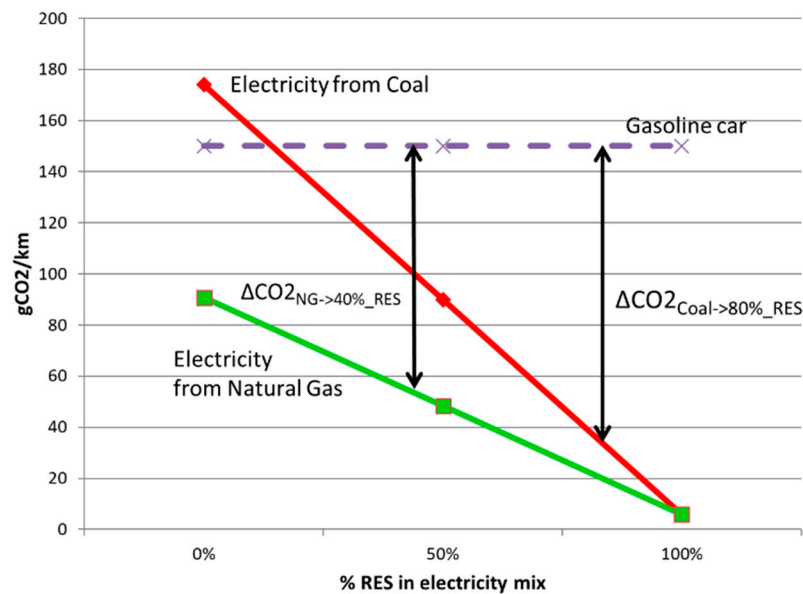
However, because of different efficiency of the end-use conversion systems, mainly ICEs vs. electric motors, the environmental comparison has to be conducted related to km driven. Since some of the transport modes, such as underground and tramway systems, are almost completely electrified worldwide, there is no need to compare them with corresponding fossil systems. Currently, the major focus is placed on emission reduction from the passenger car transport. In the following section we discuss the environmental benefits of electrification, taking BEV as an example.

As shown in Figure 18, whereas for 100% RES the CO<sub>2</sub> emissions per km driven are almost zero, they are around 170 gCO<sub>2</sub> per km driven for coal power plants, respectively about 90 gCO<sub>2</sub>/km for pure natural gas plants. For different mixes, of course, the corresponding figures are in between. The figure shows the reductions compared to gasoline cars for a share of 40% RES in a natural gas-dominated country and for 60% RES in a coal-dominated one. This graph illustrates undoubtedly that CO<sub>2</sub> reduction is higher the bigger the share of renewables in the electricity production portfolio.

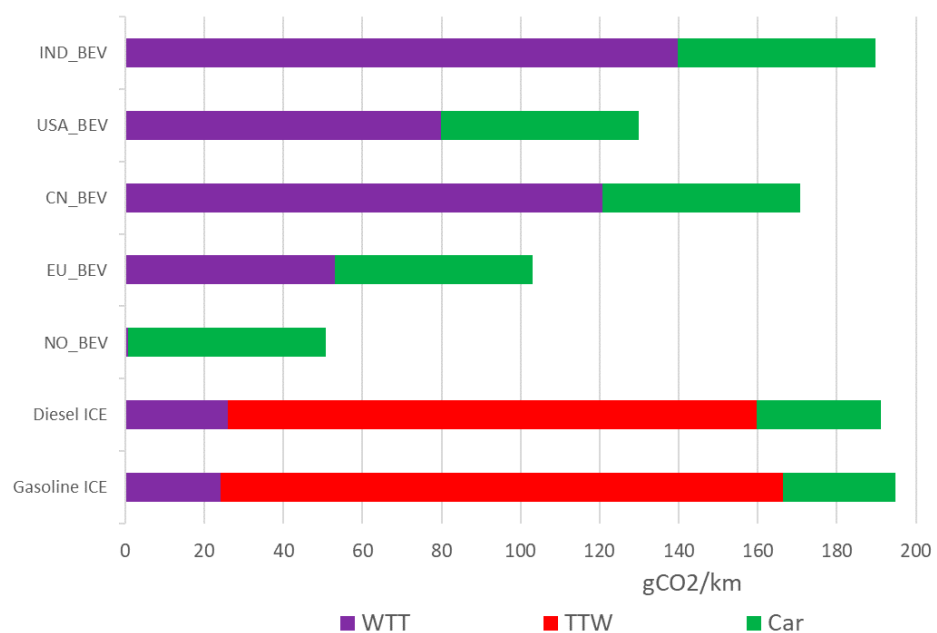
Using the same type of BEVs in different countries could lead to different total emissions, depending on the electricity used. The total CO<sub>2</sub> emissions of BEVs in various countries, compared to gasoline and diesel cars, are illustrated in Figure 19. These emissions are calculated for different countries/regions assuming an average driving range of 15,000 km driven per year. The total emissions are split up into Well-to-Tank (WTT), Tank-to-Wheel (TTW) and lifecycle car emissions, as depicted in Figure 19. The embedded emissions of car materials and manufacturing are included in the lifecycle car emissions.

As it can be seen in Figure 19, only in Norway does e-mobility really lead to a remarkable reduction in CO<sub>2</sub> emissions. In all other countries, CO<sub>2</sub> emissions from e-mobility are lower, e.g., in the EU for about 50%, in the USA for about 30%, but in India, total emissions of BEVs are almost at the same level as those of conventional cars.

However, with the increasing share of RES in electricity generation, which is set as a goal in many countries, the environmental benefits of electric vehicles will be continuously improving.



**Figure 18.** Specific WTW-CO<sub>2</sub>-emissions of fuels (excl. LCA emissions of the vehicle) in dependence of the share of RES in the electricity generation portfolio (based on [93]).



**Figure 19.** Total CO<sub>2</sub> emissions of BEVs in various countries compared to gasoline and diesel cars (based on the electricity generation mix of 2018).

**6. Conclusions**

Currently, there is a broad range of electricity use in the transport sector from individual private mobility such as electric cars, scooters and e-bikes, over different kinds of urban public mobility (e.g., underground, trolleybuses, cable cars, etc.) up to trucks and railways. Although the electrification of shipping and aviation is very limited, it is also progressing. That is to say, virtually every transport mode can be electrified.

However, a broader deployment of e-mobility in most applications will not be possible without more or less severe political interferences. The major policy measures currently used are different kinds of monetary and non-monetary incentives, which could have a direct as well as an indirect impact on the dissemination of e-mobility. For the faster deployment of e-mobility, it is important to have a combination of different instruments, such as

(i) subsidies and tax reliefs; (ii) sometimes even more important are indirect measures, such as diesel ban in cities or the introduction of emission-free zones; (iii) implementation of CO<sub>2</sub>-taxes; (iv) tighter emission standards for the whole fleet; and (v) legislation with a “right to charge” in the garages of urban apartment buildings.

A specific challenge for the faster dissemination of e-mobility is further development of batteries and a reduction of their costs. Currently, BEVs are still more expensive than petrol cars. However, fuel costs are already lower and, due to technological learning, it is expected that by 2030 the overall costs per km driven will even out. The introduction of CO<sub>2</sub> taxes would accelerate this development.

The most important issue for public applications will be affordability for the public, e.g., the municipality of a city. Of course, as the past has shown, this is not a problem in the rich cities of the Western world. But it is a severe one in emerging and even more in developing countries, where underground transport can hardly be financed and hence, cheaper solutions such as light rail systems or ropeways will be the more proper solutions.

Along with all types of e-mobility goes the issue of infrastructure development. The construction of the necessary crucial infrastructure, such as overhead lines or other networks for electricity, as well as fast charging stations, is of very high relevance. However, the deployment of the infrastructure is depends on regulations and policy frameworks, which means the involvement of different stakeholders and policymakers.

Besides financial and policy issues, topography also has an impact on the deployment of different kinds of e-mobility. For example, in regions with a hilly topography, electric ropeways could be a better solution than e-buses or e-trains. Their major advantages are the lower energy demands per person per km and lower investment costs in comparison with the underground. In cities with a very high population density, a light rail system above the roads could be a good solution, e.g., in Bangkok. In any case economics from society’s point of view will play a crucial and predominant role.

Finally, it has to be stressed once more that the major reason for promoting and implementing any type of e-mobility is to cope with the pressing environmental situation, local pollution, as well as global GHG emissions. In this context, for the environmental performance, it is of great relevance how the electricity used for e-mobility will be generated. Only if it is ensured by highly credible sources that the electricity is generated from RES, will e-mobility definitively contribute to a more environmentally benign and sustainable transport system. After all, the two absolutely crucial issues for the future deployment of all types of e-mobility are (i) political interferences; and (ii) electricity generation mix.

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