Original Research Article

GREENHOUSE GASES SCIENCE AND TECHNOLOGY

On the economics and the future prospects of battery electric vehicles

Amela Ajanovic and **Reinhard Haas**, Energy Economics Group, Vienna University of Technology (TU WIEN), Vienna, Austria

Abstract: Currently, the electrification of passenger cars is seen as one of the key strategies for heading toward a sustainable transport system. Of special interest are battery electric vehicles (BEVs), which can enable significant emission reductions if electricity used is produced from renewable energy sources. However, mainly due to their high investment costs (retail purchase price) of BEVs, they are currently not economically competitive with conventional fossil-fueled vehicles without different supporting policy measures. This paper analyzes current costs and future prospects for BEVs compared to conventional petrol cars looking at the total costs of ownership. Furthermore, the future prospects are investigated considering technological learning for BEVs, CO_2 taxes for fuels, and various other policy framework conditions such as rebates for the purchase of the BEVs. The major conclusions are as follows: (i) to improve the economics of BEVs, a very important aspect is the introduction of CO_2-based fuel taxes; (ii) regarding economics, the second important aspect is the reduction of the investment costs of the BEVs due to technological learning, especially of the battery; (iii) in addition, the introduction of CO_2-based registration taxes for the purchase of passenger cars makes sense; (iv) subsidies or rebates for the purchase of a BEV maybe a measure successful in the short term and helpful to stimulate technological learning; (v) by far, the highest uncertainty regarding the future prospects of BEVs is how fast technological learning will take place, especially for the battery, and how the future development of batteries will be. © 2020 The Authors. *Greenhouse Gases: Science and Technology* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: battery electric vehicles; economics; policies; subsidies; technological learning; total cost of ownership

Introduction

The transport sector is the main source of air pollution and one of the largest contributors to global greenhouse gas (GHG) emissions. In the EU, transport is responsible for about one quarter of the total GHG emissions. About 72% of these emissions come from road transport, mostly from passenger cars.[1]

In contrast to all other energy sectors, emissions from the transport sector are continuously increasing in spite of the broad portfolio of policy instruments implemented. To achieve significant reduction of GHG emissions, revolutionary changes in our transport system are needed.[2] These include phaseout of fossil fuel-based cars,[3] which is already announced in some European countries, for example, in Norway, Denmark, Netherlands, and Slovenia.[4]

Correspondence to: Amela Ajanovic, Energy Economics Group, Vienna University of Technology (TU WIEN), Gusshausstr. 25–27/370-3, 1040 Vienna, Austria.
E-mail: ajanovic@eeg.tuwien.ac.at
Received December 27, 2019; revised April 9, 2020; accepted April 14, 2020
Published online at Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.1985

Currently, the mature and available alternatives for conventional vehicles are electric vehicles (EVs). The shift to EVs, especially pure battery electric vehicles (BEVs), can significantly reduce noise and local air pollution, in particular in urban areas, as well as can considerably reduce global GHG emissions if the electricity comes from renewable energy sources (RES).

Currently, the electrification of mobility is perceived as one of the key strategies for a sustainable transport system. Many governments have set goals to increase the number of EVs. According to the Paris Declaration, global EV stock should be over 100 million by 2030.[5] Different types of EVs, with different advantages and disadvantages, are already available on the market. For the future, vehicles of special interest are so-called 'zero-emission' vehicles such as BEVs. They are considered as an environmentally benign alternative to conventional internal combustion engine (ICE) vehicles. However, there are currently few major barriers for their broader market penetration. Most important are (i) their high capital costs due to high costs of battery, (ii) lower driving range in comparison to conventional vehicles, and (iii) limited availability of charging infrastructure. Due to these barriers, it is very important to provide supporting policy framework to increase attractiveness of BEVs and their economic competiveness with fossil-fueled cars.

The core objective of this paper is to analyze the current costs and economics of BEVs, as the major barriers to their faster market penetration. Moreover, major policies implemented in European countries are documented and evaluated. Of special interest are the future prospects of BEVs until 2050, from the economic point of view of the average European country within a dynamic framework in comparison to those of conventional passenger cars.

This paper is based on a comprehensive literature review and builds on our previous works,[6,7] with the major focus on pure BEVs. Over the past years, interest in electrification of mobility has been increasing. One of the first comparative analyses of different types of EVs and their role in the future transport system has been conducted by Offer *et al.*[8] The effect of incentives for EVs in the EU has been analyzed by Vilchez and Thiel.[9] They have stressed importance of subsidies for EVs in the mid-term. However, in the majority of countries, BEVs are still more expensive than their ICE pairs.[10] The future prospect of EVs in Germany in relation to the total costs of ownership (TCO) has been evaluated by Bubeck *et al.*,[11] indicating that to achieve cost competitiveness for BEVs, considerable subsidies are necessary. Breetz and Salon have analyzed TCO for conventional, hybrid, and EVs in 14 US cities showing that it is very challenging for BEVs to achieve unsubsidized competitiveness with conventional cars.[12] Moon and Lee have investigated an optimal EV investment model for users based on TCO using empirical data from the Korean automobile market. They found that EVs are, at the current fuel price level, already cost-effective in the Korean market.[13] In the past, TCO have been calculated in various studies considering different types of EVs, different countries and regions, as well as different vehicle categories and user types.[14–17] However, due to the significant reduction of battery prices, and consequently BEV prices over the past years, and continuously changeable policy frameworks in most of the countries, TCO have to be considered in a dynamic framework. They are good tools to show the impact of different parameters on the total cost. In this paper, special focus is laid on the impact of average vehicle kilometers driven per year.

First in this paper, recent developments regarding the use of BEVs in European countries are documented and analyzed in the next section. An economic assessment of BEVs is given in the third section. In the fourth section, the major policy measures implemented are discussed and evaluated. The future prospects for the economic competitiveness of BEVs are analyzed in the fifth section. Finally, major conclusions are provided in the sixth section.

Battery electric vehicles: state of the art

Since EVs have potential to reduce local air pollution, noise, and global GHG emission, interest in their use is continuously increasing. However, the use of EVs is currently largely driven by different supporting policy measures, which should make EVs more attractive and more economically competitive with conventional ICE vehicles. Moreover, these measures should also encourage car manufactures to scale up production. In addition, with implementation of low- or zero-emission zones, with limited or prohibited access for ICE vehicles, in many European cities, interest in zero-emission vehicles, such as BEVs, is increasing. As shown in Fig. 1, stock of BEVs in European countries has been increasing continuously since 2010.

Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985

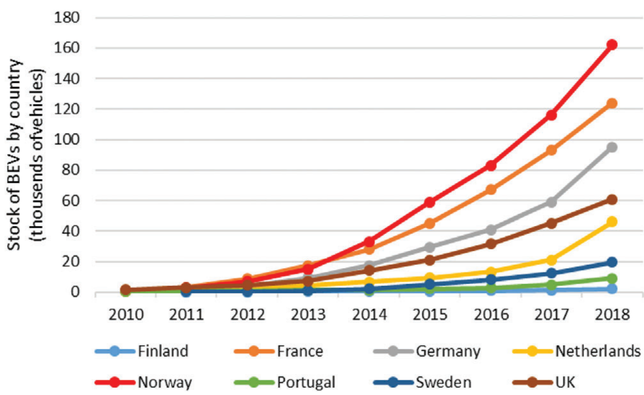

Figure 1. Development of the stock of BEVs in selected European countries (data source: IEA[4]).

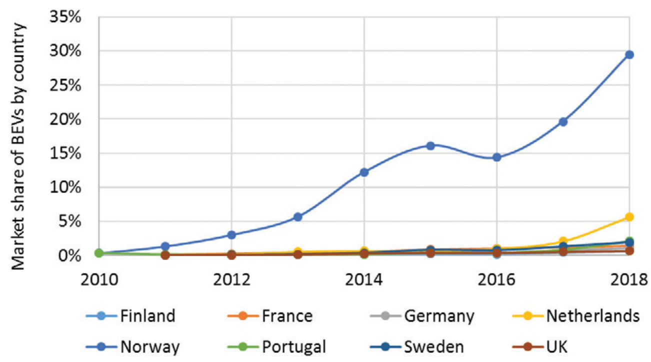

Figure 3. Market share of new purchased BEVs in selected European countries (data source: IEA[4]).

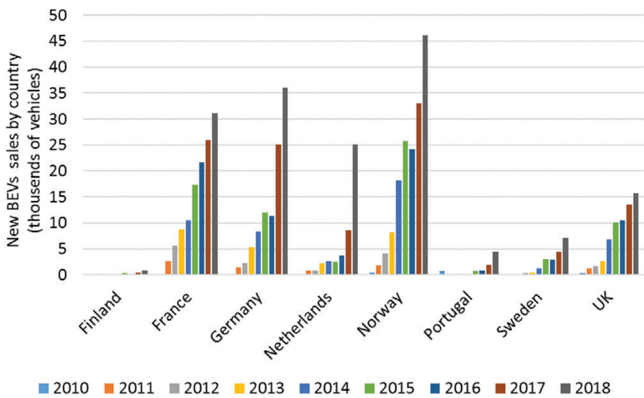

Figure 2. BEV sales in selected European countries (data source: IEA[4]).

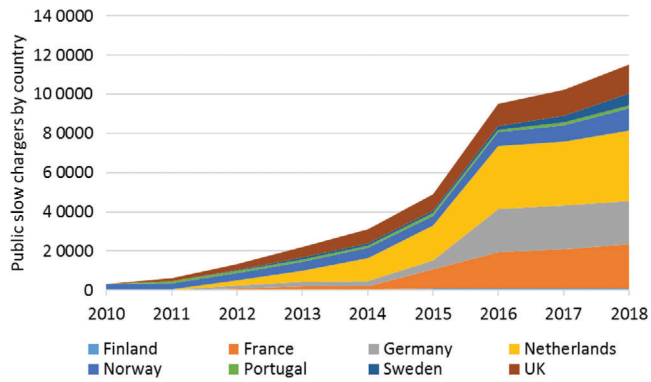

Figure 4. Publicly accessible slow chargers in selected European countries (data source: IEA[4]).

In 2018, the global stock of BEVs reached 3.3 million.[4] China accounts for about 54% of the total stock. In Europe, the largest number of BEVs is in Norway. However, this is just about 5% of the global stock. In the second place is France, followed by Germany with 124,010 and 95,000 BEVs, respectively. Figure 1 shows the development of the stock of BEVs in few European countries that have the largest number of BEVs.

Figure 2 shows a year-to-year growth in BEV sales in the period 2010–2018. In 2018, Norway was the largest BEV market in Europe with sales of 46,140 units, followed by Germany and France. In Europe, the increase in BEV sales is different from year to year, as well as there are significant differences between countries. The dynamic behavior of EV sales is mostly the result of the changeable supporting policy framework.[9]

Although BEV sales are increasing in all countries, there is a significant difference in their market share. Figure 3 illustrates the market share of BEVs in selected countries. It is obvious that Norway is the leader in terms of market share of BEVs, with almost 30%, followed by the Netherlands, with 5.65% market share. In all other countries, market share of BEVs is very low, in the range between 0.64% (Finland) and 2.08% (Portugal).

Limited availability of public charging infrastructure is often seen as a barrier for the faster penetration of BEVs. However, as depicted in Fig. 4, despite the high number of BEVs in use, the number of publicly accessible slow charging stations in Norway is considerably lower than in the Netherlands, France, and Germany. One charger per ten EVs is the ratio recommended by the European Union Alternative Fuels Infrastructure Directive.[18] Still, many leading countries in terms of deployment of BEVs remain below one charger per ten vehicles. The ratio in Norway is one charger per 20 EVs. On the other hand, in the Netherlands this ratio is about one charger per four to eight EVs.[4]

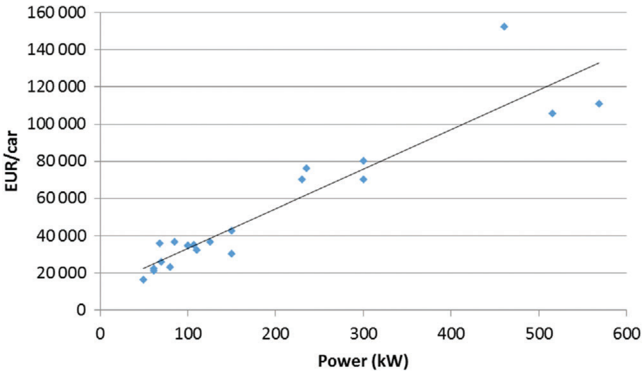

Figure 5. Investment costs of BEV depending on the capacity of the car (as of 2019).[19–22]

If we discuss the costs of any type of car, it is obvious that they will depend on the size of the car. That is also true for the BEVs as can be seen from Fig. 5. This figure depicts that there is almost a linear relationship between the capacity of the car (kW) and the investment costs. However, for our further analysis we refer to average car capacities of 80 kW for BEVs, as well as for petrol vehicles.

Yet, it is also of interest how investment costs of BEVs developed in recent years. This effect is depicted in Fig. 6 for some brands of BEVs from 2009 to 2019. As shown in the figure, there was a remarkable reduction in investment costs of some cars. Overall, it can be stated that from 2009 until 2019, an average investment cost reduction of about 40% took place. Note that the technical configurations of vehicles may also have changed in this period.

Economic assessment

In spite of significant improvement of battery characteristics and their cost reductions, high purchase prices of BEVs are still seen as one of the major barriers for their faster penetration. However, to evaluate the economics of BEVs in comparison to conventional internal combustion vehicles, it is important to calculate TCO. The TCO is an often used method to help car buyers and owners to determine the direct and indirect costs of mobility. This calculation method contributes to better understanding of the interactions between financial incentives and sale.[10]

To evaluate the economics of BEVs, we compare the TCO per 100 km driven. In this context, different driving distances play a role. In detail, we calculate with 8000, 16 000, and 24 000 km driven per year. The costs of car ownership (C_{TCO}) per kilometer driven are calculated as

$$C_{TCO} = \frac{IC \cdot \alpha}{vkm} + P_e \cdot FI + \frac{C_{O\&M}}{vkm} \quad (€\ 100\ km^{-1} driven) \tag{1}$$

where IC is the investment costs of vehicle (€ car^{-1}); α, the capital recovery factor; vkm, the specific vehicle kilometers driven per year (km car·yr^{-1}); P_e, the energy price inclding taxes (€ kWh^{-1}); $C_{O\&M}$, the operating and maintenance costs (€ yr^{-1}); and FI is the energy consumption (kWh 100 km^{-1}).

Total investment costs depend on the net purchase price (C_{pp}) and additional taxes such as registration tax (τ_{REG}) and value-added tax (VAT) on cars (τ_{VAT_car}):

$$IC = C_{pp} + \tau_{REG} + \tau_{VAT\_car} \ (€\ car^{-1}) \tag{2}$$

The capital recovery factor (α), which is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time, is calculated using an interest rate (i) and the depreciation time (n). The annuity method is used to make the depreciation and calculate annual capital costs using the same capital recovery factor, based on 8 years of depreciation time, for the battery as well as for the car. The most of the currently provided battery warranties are given for the period of 8 years covering all the analyzed travel distances in this paper, from 8000 to 24 000 km driven per year. We use an interest rate of 5%, which is a common value and which represents the interest that would have to be paid to a bank if a loan was taken.

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

In this paper, the resale value of the cars is not considered.

The energy price depends on the cost of energy used in vehicles C_e, and possible taxes such as VAT, excise, and CO_2 taxes:

$$P_e = C_e + \tau_{CO_2} + \tau_{VAT} + \tau_{exc} \tag{4}$$

A specific issue is the dynamic development of the energy prices over time. Figure 7 depicts the historical energy costs for petrol and electricity per kilowatt-hour energy over the time period 1990–2018. As seen from this figure, there are two important findings: on the one hand, the real prices (of 2015) for both fuels are

Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985

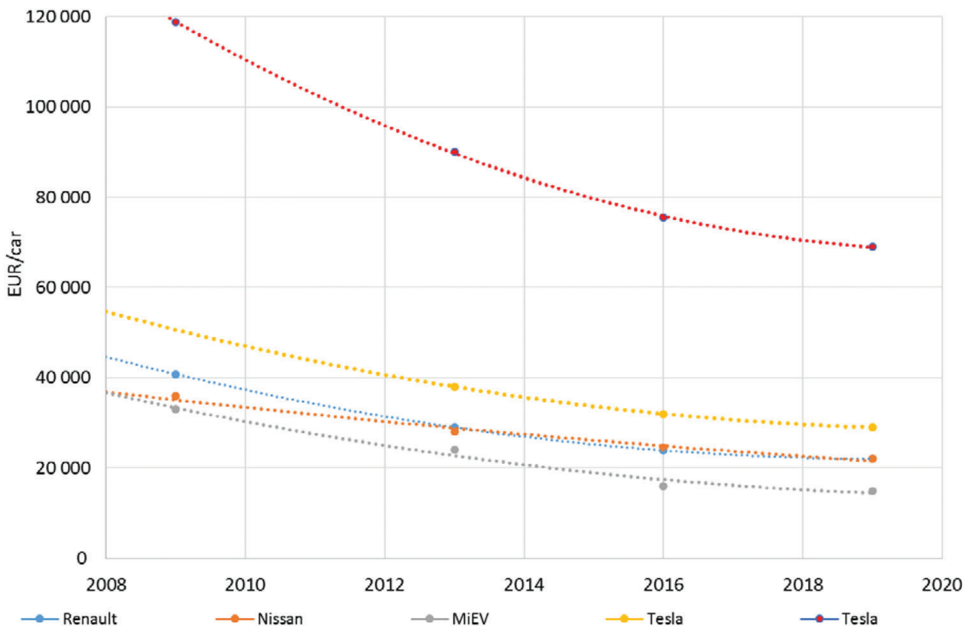

Figure 6. Development of investment costs of different brands of BEVs, period 2009 to 2019 based on own historical database.

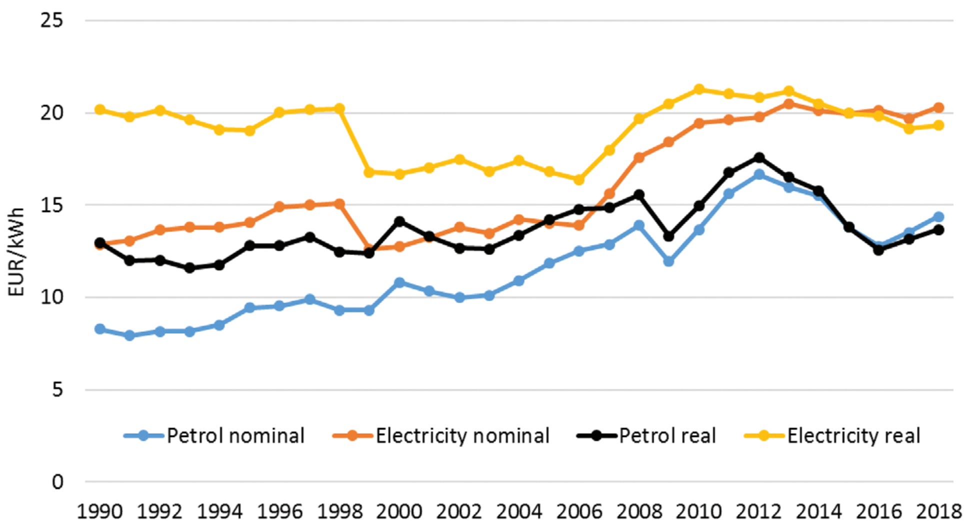

Figure 7. Development of the energy prices over the time period 1990–2018 (in EUROs of 2015).[23,50]

virtually the same at the beginning and at the end of the period. On the other hand, the volatility is remarkable for both energy carriers.

Figure 8 depicts the energy costs for petrol cars and BEVs for driving 100 km based on the data for the year 2018, as shown in Fig. 7. As seen from this figure, especially the excise taxes vary in a wide range. The total maximum energy prices are around 40% higher than the lowest ones. In the further calculation of the TCO, we use the average numbers of both types of vehicles.

Using Eqn (1), we can now calculate the TCO of conventional gasoline ICE vehicles and BEVs for the year 2018. As we suspect that the kilometer driven per year is a major impact parameter on the economic performance, we vary this parameter between 8000 and 24 000 km year^{-1}. The results of this analysis are documented in Fig. 9.

The major findings from this figure are as follows:

i. For both vehicle types, the share of the capital costs in the total costs is the highest.

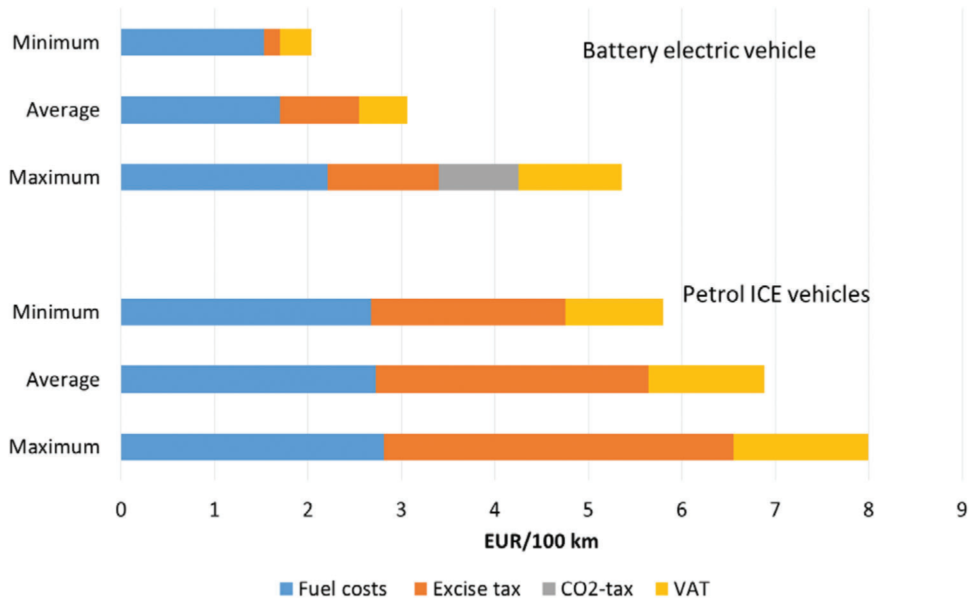

Figure 8. Minimum, average, and maximum energy costs including taxes per 100 km driven in European countries, 2018.

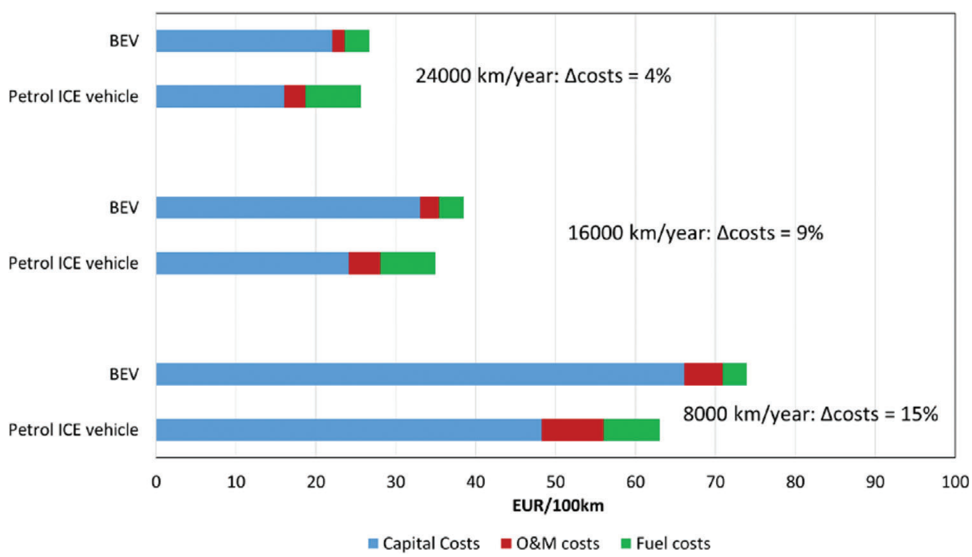

Figure 9. TCO of petrol ICE vehicles and BEVs for the average of European countries for different driving ranges, 2018 (car power: 80 kW).

ii. Clearly, the major reason for the unfavorable economic performance of the BEV is the significantly higher investment costs.
iii. The energy costs of BEVs are, on average, already lower than those of petrol cars. However, there are significant differences in electricity and petrol prices across countries; see Figs. 10 and 11.
iv. The total costs depend greatly on the number of kilometers driven per year. While for 8000 km driven per year the total costs of BEVs are 15% higher in comparison to conventional vehicles, they are only 4% higher for 24 000 km. That is, if BEVs are used in car sharing or as taxis with higher driving ranges, their economic performance will be considerably better.

The economics of BEVs depends also on the ratio between petrol and electricity prices in individual countries. As Fig. 12 depicts, this ratio is more

Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985

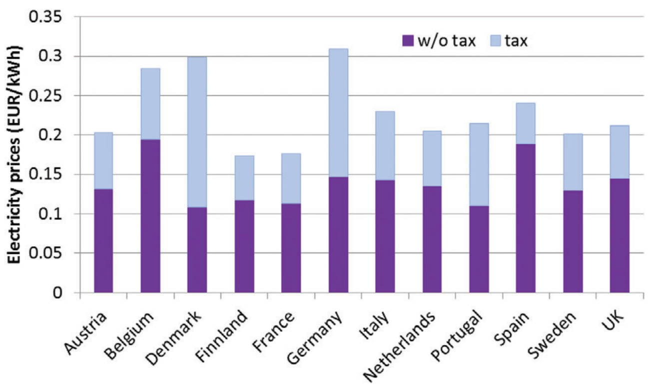

Figure 10. Electricity prices in selected countries, 2019.[23]

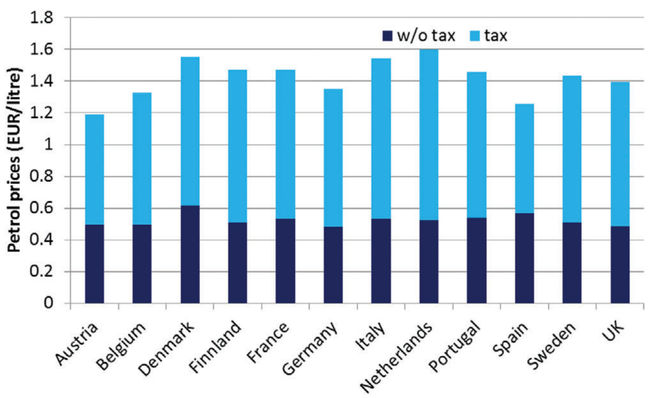

Figure 11. Petrol prices in selected countries, 2019.[24]

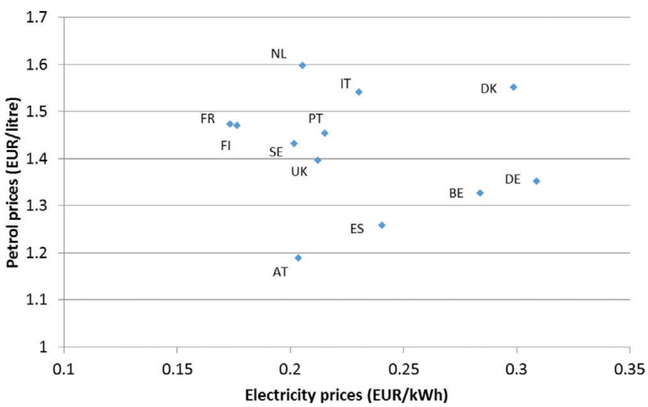

Figure 12. Relation between petrol prices and household electricity prices in selected European countries in 2018.[23,24]

favorable in countries such as the Netherlands and France and less favorable in Germany and Belgium.

Policy framework

Owing to the currently unfavorable economic performance of BEVs in comparison to conventional ICE vehicles, it is important to use different promotion measures to increase the purchases of BEVs. Worldwide, many countries have already provided supporting policy measures for BEVs while they are seen as technology, which can contribute to the reduction of local air pollution, noise, and global GHG emissions.

Due to the pressing environmental problems, many European policy goals are directed toward GHG emission reductions and increase the use of RES. Some of the policies and goals support the use of BEVs indirectly, for example, EU CO_2 emissions regulation (no. 333/2014),[25] the European climate and energy package,[26,27] and the White Paper on Transport.[28]

In this paper, a range of existing measures that have a direct or indirect impact on the uptake of BEVs are documented and evaluated. Some of them are ban on ICE cars, subsidies for the purchase of EVs, different tax benefits for EVs, and financial support for charging infrastructure.

Currently, a direct quota for BEVs is not implemented in Europe. However, the EU introduced a CO_2 target for the new passenger cars (regulation 443/2009).[29] This measure is supporting the production of low-carbon vehicles, especially BEVs since targets set are hardly achievable without increasing the use of zero-emission vehicles.

The first mandatory target for the year 2015 – 130 g of CO_2 emitted per kilometer – was already achieved in 2013. The next target is 95 g CO_2 km^{-1} in 2021. For the achievement of this target, it will be necessary to increase the use of alternative automotive technologies such as EVs. Recently, more ambitious targets and tougher emission testing procedures are set for 2025 and 2030.[30]

Other measures that indirectly support the use of BEVs are ban on ICE vehicles. Standards or bans that prohibit vehicles with certain technological features are a common regulatory measure used in transport policy.[31] A ban on conventional ICE vehicles should encourage the development, production, and purchase of alternative automotive powertrains with low and zero emissions.

Many cities have already introduced low or zero-emission zones making restrictions in the use of fossil-fueled vehicles. Moreover, recently a range of countries, as a response to pressing environmental problems, announced plans to ban new ICE vehicles in future. Norway plans to ban the sale of new ICE cars starting already in 2025. In addition, some EU countries, the Netherlands, Ireland, and Slovenia, have announced the ban on ICE vehicles starting from 2030.[4]

The announcement of bans on conventional cars sends a clear signal to the car manufacturers. Therefore, it can be expected that the manufacturing of BEVs will increase in the next years. Many car manufacturers have already announced their plans to sell many of their future models as electric versions.[4,32]

Due to the diesel-emission scandal as well as the current restriction on diesel cars in some urban areas, the sale of new diesel cars in the EU has dropped significantly in the last few years.[33] However, since BEVs are still too expensive for most users, a shift from diesel to petrol cars can be observed at this time.[34]

To change this and make BEVs more attractive and affordable, many EU countries offer different grants (nonrepayable funds that consumers receive at the point of EV purchase) for their purchase. The grants could be an effective method to increase BEV use, if they are sufficiently large. Higher impact could be reached if they target smaller and cheaper EVs where the incentive makes a significant difference for the buyer.[35] Moreover, they are often combined with other measures such as tax advantages or support for the charging infrastructure.[36] Many EU countries are already using tax exemptions or reductions (e.g., for the VAT and/or registration tax) with the goal to reduce the total costs of BEVs.

Measures and policies applied at the point of BEV purchase (e.g., tax exemptions) are the most effective financial incentives, particularly in countries with high tax rates for ICE vehicles, such as Norway and the Netherlands.[2,37] Benefits at a later stage, such as exemptions or reductions of the annual circulation tax, often do not have a strong price signal and have low impact on the purchase of BEVs.[38] The maximal incentives provided in the EU for new BEVs are shown in Table 1.

Table 1. Maximal incentives for private passenger BEVs in the selected countries (data source: ACEA[39]).

Country	Maximal incentives for private BEVs
Romania	10 000 €
Slovenia	7500 €
France	6000 €
Italy	6000 €
Spain	5500 €
Ireland	5000 €
Germany	4000 €
UK	4189 € (3500 GBP)
Austria	3000 €
Finland	2000 €
Sweden	5672 € (60 000 SEK)

Comparison of leading EV policies in Europe is conducted in several studies,[40–42] indicating need for tax benefits and incentives for BEVs in this early stage. Currently, the consumer acceptance of BEVs is significantly influenced by vehicle taxation and provided incentives in specific countries.[43,44]

Future prospects for BEVs

It is of specific interest to analyze the future prospects of BEVs from an economic point of view. In this context, the most important is the development of the investment costs.

The method of approach applied in this work is based on a scenario with favorable conditions for the development of the energy performance of conversion efficiencies in the whole energy service mobility providing chain. We conduct a dynamic technical and economic analysis and investigate when in the future BEVs could become economically competitive compared to conventional gasoline and diesel cars.

To capture the dynamic effects of changes in investment costs of powertrains over time, we apply the approach of technological learning. The concept of technological learning was first introduced over 70 years ago.[45] This approach is often used in the literature to identify whether with increasing capacities deployed, a decrease in investment costs took place.[46–48] We have considered technological learning using the following equation[49]:

$$\mathrm{IC}_{\mathrm{New}}\left(x_t\right) = \mathrm{IC}\left(x_{t_0}\right) \cdot \left(\frac{x_t}{x_{t_0}}\right)^{-b} \tag{5}$$

where $\mathrm{IC}_{\mathrm{New}}(x_t)$ is the investment cost of new technology, b is a learning index, $\mathrm{IC}(t_0)$ is the investment cost at time t_0, and x refers to the cumulative number of vehicles at times t and t_0.

The learning index b defines the effectiveness with which learning process takes place. For example, if the learning index is 20%, this means that with a doubling of the cumulated number of cars produced, their investment costs decrease by 20%.

Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985

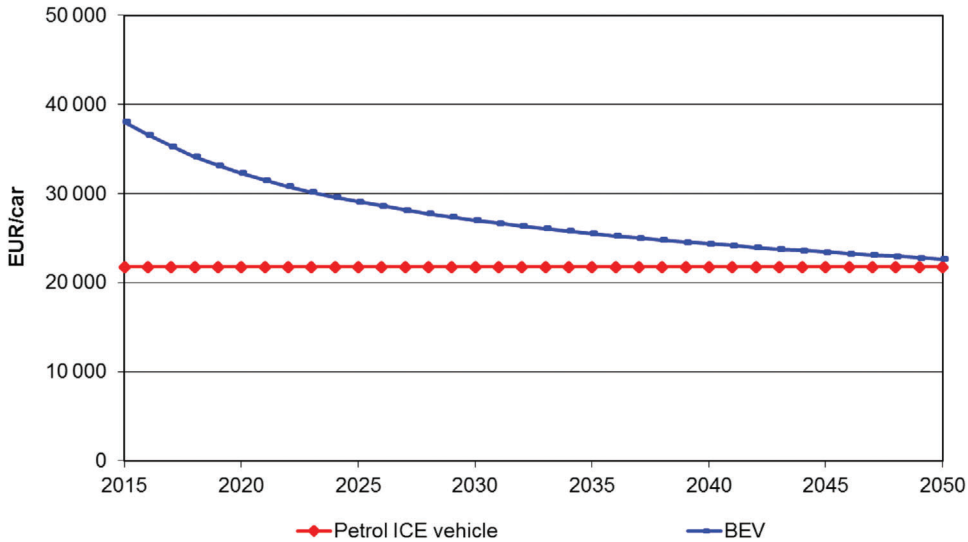

Figure 13. Development of the investment costs of BEVs and ICE vehicles over time considering technological learning and service increases.

With respect to the future development of the investment costs of alternative powertrains, it is expected that they will be reduced through technological learning. Next, in our model, we split up specific investment costs $IC_t(x_t)$ into a part that reflects the costs of conventional mature technology components $IC_{Con_t}(x_t)$, for which additional cost reduction due to technological learning cannot be expected, and a part of the new technology components $IC_{New_t}(x_t)$, for example, batteries and fuel cells for which we can expect further cost reduction through learning effects.

$$IC_t(x_t) = IC_{Con_t}(x_t) + IC_{New_t}(x_t) \quad (6)$$

where $IC_{Con_t}(x_t)$ is the specific investment cost of conventional mature technology (€ car^{-1}) and x_t is the cumulative number of vehicles up to year t; for $IC_{New_t}(x_t)$, we use (5) to express an experience curve.

Based on technological learning, BEVs have already become cheaper over the past years. Figure 13 shows the development of the investment costs of BEVs and ICE vehicles in the period 2015–2050. The values considered refer to an average 80 kW car. Conventional cars are mature technology so that further cost reduction is not considered. However, it is important to note that increasing average power of cars and improvements in the service quality in cars (e.g., the electronics) have virtually eaten up the largest part of the cost savings that have incurred for the 'naked' car due to learning. In the contrary, BEVs have still significant learning potential.

For the economic analysis, we consider investment costs, operating and maintenance costs, fuel costs, and the relevance of CO_2 taxes in the cost structure. Moreover, we use different numbers of specific kilometres driven per year for different car categories. Our analysis starts with the fuel costs. Figure 14 compares the scenarios for the development of the fuel costs (including taxes) of the service mobility per 100 km driven from 2010 to 2050. For the period 2010–2018, the historical figures at prices of 2015 from Fig. 7 are taken.

In our scenario, CO_2 taxes replace excise taxes and increase up to 2050 by 1.5 cent kg^{-1} CO_2 and year. In addition, the costs of petrol and diesel increase by 3% per year. The resulting costs in 2050 (in prices of 2015) are documented in Fig. 14. The energy costs for driving remain the cheapest for electricity. Due to the introduced CO_2 taxes, price increases are highest for the fossil fuel driven vehicles and the gap between petrol and electricity prices is continuously increasing.

Figure 15 depicts the fuel costs for petrol cars and BEV for driving 100 km based on the above scenario for the year 2050. As seen from this figure, especially the introduced CO_2 taxes play a considerable role. The total maximum fuel prices are more than 50% higher than the lowest ones. In the further calculation of the TCO, we use the average numbers of both types of vehicles.

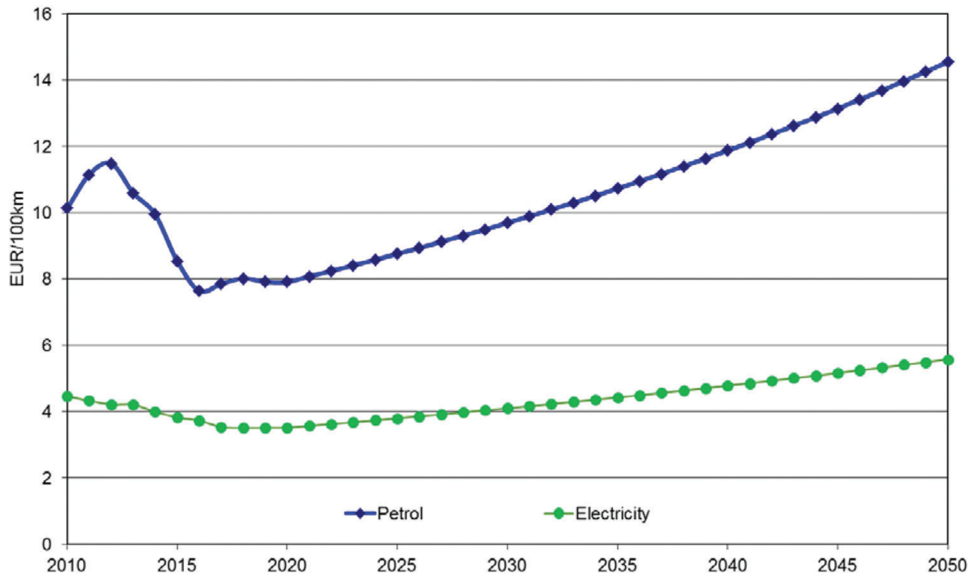

Figure 14. Scenario of the development of fuel costs including taxes per 100 km in the period 2018–2050 (in EUROs of 2015). Note that the numbers from 2000 to 2018 are historical values according to Fig. 7.

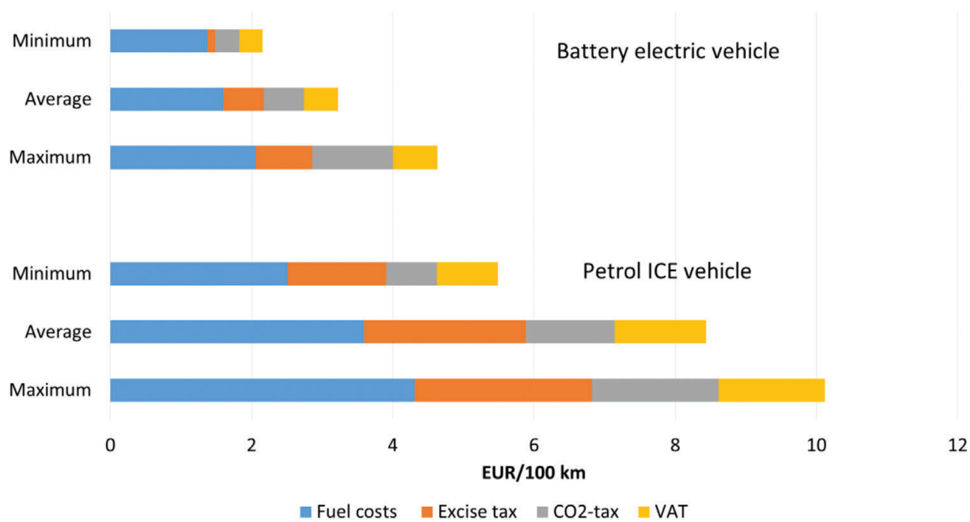

Figure 15. Minimum, average, and maximum energy prices including taxes per 100 km driven in European countries, 2050.

Using Eqn (2), we can now calculate the TCO of petrol and BEVs for the year 2050. As we suspect again that the kilometer driven per year has a major impact on the economic performance, we vary this parameter between 8000 and 24 000 km year^{-1}. The results of this analysis are documented in Fig. 16.

Figure 16 describes the cost structure of total costs of driving for petrol cars and BEV in 2050. We can see that the advantages of alternative powertrains regarding lower fuel costs by 2050 compensate the higher capital costs in the case of a high number of kilometers driven.

The major findings from this figure are as follows:

i. Also in the future, the capital costs will have the largest impact on the TCO for both vehicle types. Yet, calculation for the highest number of kilometers driven in 2050 shows that BEVs could be more competitive due to the introduction of CO_2-based taxes on fossil fuels.

  Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985

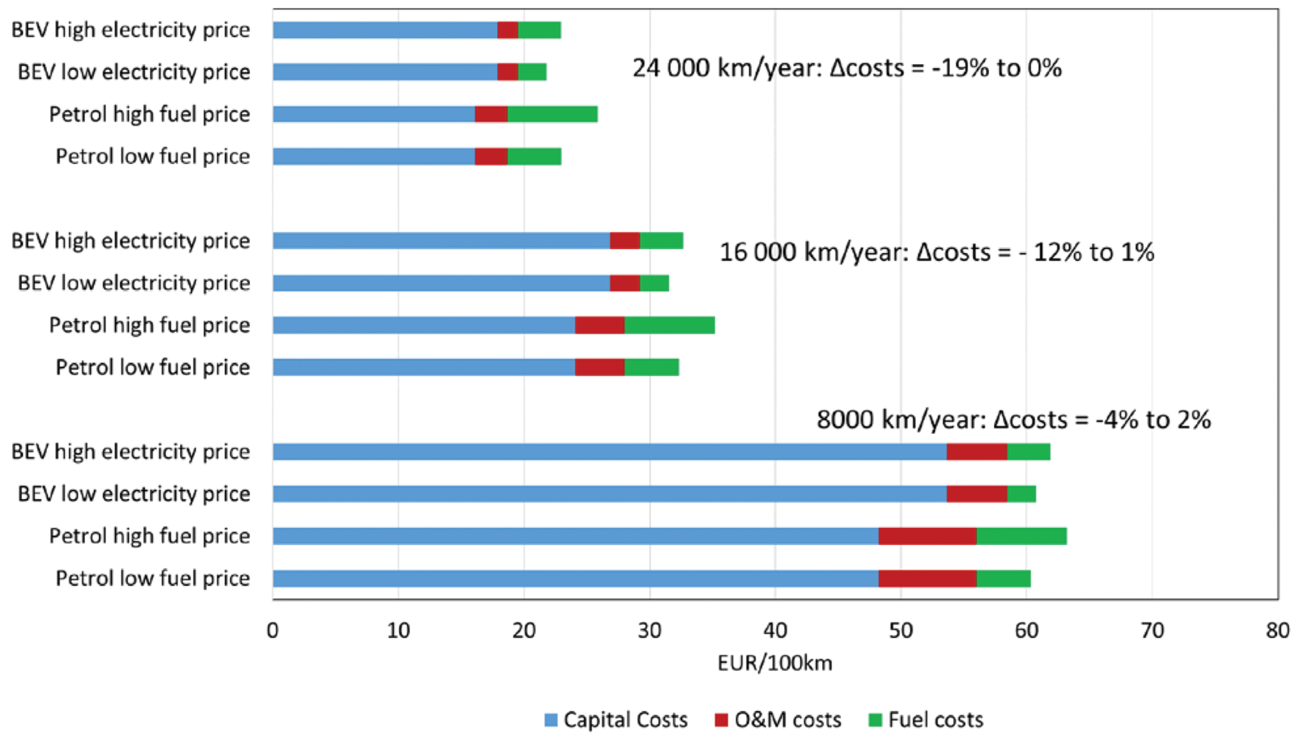

Figure 16. TCO of petrol ICE vehicles and BEVs for the average of European countries for different driving ranges in 2050 for different energy prices (car power: 80 kW).

ii. In 2050, in the case of 8000 km driven BEVs and a combination of low petrol prices and high electricity prices (according to Fig. 15) their TCO could be for about 2% higher than those of conventional cars. However, in the combination of high petrol prices and low electricity prices, already at this low number of kilometers driven per year BEVs could be competitive with conventional vehicles, with 4% lower total costs.

iii. The fuel costs of BEVs are on average lower than those of petrol cars. However, these costs could vary due to different taxation and fluctuation in electricity and petrol prices across Europe.

iv. The kilometer driven per year is a very sensitive parameter as seen in Fig. 16. In the case of 8000 km driven per year, the TCO for BEVs could be about 4% lower than for petrol vehicles in a favorable case (low electricity prices and high petrol prices). However, in the case of 24 000 km driven per year, total costs per kilometers driven are much lower for both vehicle types. In the worst case, BEVs have equal total costs to the petrol ICE vehicles, and in the best case their total costs could be even 19% lower compared to petrol cars.

Conclusions

Currently, the electrification of passenger cars is considered one of the key strategies for heading toward a sustainable transport system. To accelerate this transformation, it is essential to improve the economics of BEVs and especially to reduce their investment costs through technological learning, especially regarding battery. Their operating costs are already significantly lower than those of conventional cars. Moreover, to make BEVs more competitive with conventional petrol vehicles, it is important to introduce CO_2-based fuel taxes. This tax should make the operating costs of conventional cars more expensive, and also it should ensure that the electricity used in BEVs is generated from RES. In addition, the introduction of CO_2-based registration taxes on passenger cars can significantly increase the attractiveness of all low-carbon technologies. Subsidies or rebates on the purchase of BEVs may be successful measures in the short term and helpful to stimulate technological learning. However, it would neither be possible to retain these over a longer period nor would they have a significant long-term impact on the additional market penetration of BEVs because most subsidies would be given to individuals who would purchase BEVs even without subsidies.

Regarding the future economic competitiveness of BEVs compared to conventional vehicles, various scenarios are possible. In the most favorable case, in the case of long driving distances, BEVs will become competitive much earlier than when used for short driving distances. Finally, by 2050 the total driving costs of both vehicle categories will even out, or may even become cheaper for BEVs if the electricity used is generated from RES, and not the subject of CO_2 tax.

The major uncertainty regarding the future deployment of BEVs is how fast technological learning will take place, especially regarding the battery, and how the future development of battery technologies and designs will be.

References

1. European Commission, *Statistical Pocketbook. EU Transport in Figures* (2019). Available: https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2019_en [accessed 1 April 2019].
2. Velten EK, Stoll T and Meinecke L, *Measures for the Promotion of Electric Vehicles*. Ecologic Institute, Berlin, Commissioned by Greenpeace e.V. (2019).
3. DLR (Deutsches Zentrum für Luft- und Raumfahrt), *Development of the Car Fleet in EU28+2 to Achieve the Paris Agreement Target to Limit Global Warming to 1.5°C* (2018). Available: http://www.greenpeace.org/belgium/Global/belgium/report/2018/20180907_GP_EUCarFleet_1.5.pdf [accessed 1 April 2019].
4. IEA, *Global EV Outlook 2019: Scaling-Up the Transition to Electric Mobility*. International Energy Agency, Paris (2019).
5. United Nations, *The Paris Declaration on Electro-Mobility and Climate Change and Call to Action*. Available: https://unfccc.int/news/the-paris-declaration-on-electro-mobility-and-climate-change-and-call-to-action [accessed 1 April 2019].
6. Ajanovic A, Jungmeier G, Beermann M and Haas R, Driving on renewables – on the prospects of alternative fuels up to 2050 from an energetic point-of-view in EU countries. *J Energ Resour Technol* **135**(3) (2013). https://doi.org/10.1115/1.4023919 [accessed 1 April 2019].
7. Ajanovic A, The future of electric vehicles: prospects and impediments. *WIREs Energy Environ* **4**(6):521–536 (2015).
8. Offer GJ, Howey D, Contestabile M, Clague R and Brandon NP, Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy* **38**:24–29 (2010).
9. Vilchez JJG and Thiel C, The effect of reducing electric car purchase incentives in the european union. *World Electr Vehicle J* **10**:64 (2019).
10. Lévay PZ, Drossinos Y and Thiel C, The effect of fiscal incentives on market penetration of electric vehicles: a pairwise comparison of total cost of ownership. *Energy Policy* **105**:524–533 (2017).
11. Bubeck S, Tomaschek J and Fahl U, Perspectives of electricmobility: total cost of ownership of electric vehicles in Germany. *Transport Policy* **50**:63–77 (2016).
12. Breetz HL and Salon D, Do electric vehicles need subsidies? Ownership costs for conventional hybrid, and electric vehicles in 14 U.S. cities. *Energy Policy* **120**:238–249 (2018).
13. Moon S and Lee D-J, An optimal electric vehicle investment model for consumers using total cost of ownership: a real option approach. *Appl Energy* **253** (2019). https://doi.org/10.1016/j.apenergy.2019.113494 [accessed 1 April 2019].
14. Palmer K, Tate JE, Wadud Z and Nellthorp J, Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. *Appl Energy* **209**:108–119 (2018).
15. Propfe B, Kreyenberg D, Wind J, Schmid S, Market penetration analysis of electric vehicles in the German passenger car market towards 2030. *Int J Hydrog Energ* **38**, 5201–5208 (2013).
16. Sharma R, Manzie C, Bessede M, Brear MJ and Crawford RH, Conventional, hybrid and electric vehicles for Australian driving conditions – part 1: technical and financial analysis. *Transp Res Part C* **25**:238–249 (2012).
17. Offer GJ, Contestabile M, Howey DA, Clague R and Brandon NP, Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK. *Energy Policy* **39**:1939–1950 (2011).
18. EUR-Lex, *Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the Deployment of Alternative Fuels Infrastructure* (2014). Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=ENof alternative fuels infrastructure.
19. Kelley Blue Book, *2019 Nissan Leaf vs. 2019 Volkswagen eGolf Comparison* (2019). Available: www.kbb.com/articles/comparison/nissan-leaf-vs-volkswagen-egolf-comparison/ [accessed 15 February 2020].
20. Energysage, *How Much Do Electric Cars Cost*? Available: www.energysage.com/electric-vehicles/costs-and-benefits-evs/electric-car-cost/ [accessed 15 February 2020].
21. Vinkhuyzen M, *European Electric Vehicle Invasion – Winners, Big Winners, & Champions* (2019). Available: https://cleantechnica.com/2019/01/13/new-electric-cars-on-the-market-in-europe-2019/[accessed 15 February 2020].
22. Elektroauto-News, *Elektroauto Preise: Preise für Elektroauto-Modelle im Überblick*. Available: www.elektroauto-news.net/ [accessed 15 February 2020].
23. European Commission, *Eurostat Database*. Available: https://ec.europa.eu/eurostat/data/database [accessed 1 April 2019].
24. FuelsEurope, *Fuel Price Breakdown*. Available: https://www.fuelseurope.eu/knowledge/refining-in-europe/economics-of-refining/fuel-price-breakdown/ [accessed 15 February 2020].
25. EUR-Lex, *Regulation (EU) No. 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No. 443/2009 to Define the Modalities for Reaching the 2020 Target to Reduce CO_2 Emissions from New Passenger Car* (2014). Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0333&from=EN [accessed 1 April 2019].

26. European Commission, *2020 Climate & Energy Package* (2018). Available: https://ec.europa.eu/clima/policies/strategies/2020_en [accessed 1 April 2019].
27. European Commission, *2030 Climate & Energy Framework* (2018). Available: https://ec.europa.eu/clima/policies/strategies/2030_en [accessed 1 April 2019].
28. European Commission, *Roadmap to a Single European Transport Area: Towards a Competitive and Resource Efficient Transport System* (2011). Available: https://doi.org/10.2832/30955 [accessed 1 April 2019].
29. EUR-Lex, *Regulation 443/2009 Regulation (EC) No. 443/2009 of the European Parliament and of the Council of 23 April 2009 Setting Emission Performance Standards for New Passenger Cars as Part of the Community's Integrated Approach To Reduce CO_2 Emissions from Light-Duty Vehicles* (2009). Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009R0443 [accessed 1 April 2019].
30. European Commission, *Proposal for a Regulation of the European Parliament and of the Council Setting Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles as Part of the Union's Integrated Approach to Reduce CO_2 Emissions from Light-Duty Vehicles and Amending Regulation (EC) No. 715/2007 (Recast)* (2018). Available: https://eurlex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017PC0676R(01) [accessed 1 April 2019].
31. Kazmierczyk P, *Sustainable Consumption and Production in South East Europe and Eastern Europe, Caucasus and Central Asia – Joint UNEP-EEA Report on the Opportunities and Lessons Learned* (2007), Available: https://www.eea.europa.eu/publications/eea_report_2007_3 [accessed 1 April 2019].
32. Burch I and Gilchrist J, *Survey of Global Activity to Phase Out Internal Combustion Engine Vehicles*. Centre for Climate Protection (2018). Available: https://theclimatecenter.org/wp-content/uploads/2018/09/Survey-on-Global-Activities-to-Phase-Out-ICE-Vehicles-FINAL.pdf [accessed 1 April 2019].
33. Kodjak D, *How to Think About Vehicle Bans: An Update After Two Major European Judicial Decisions*. International Council on Clean Transportation, Washington, DC (2018). Available: https://www.theicct.org/blog/staff/how-think-about-vehicle-bans-update-after-two-majoreuropean-judicial-decisions [accessed 1 April 2019].
34. ACEA (European Automobile Manufacturers' Association), *Share of Diesel in New Passenger Cars* (2019). Available: https://www.acea.be/statistics/tag/category/share-of-diesel-in-new-passenger-cars [accessed 1 April 2019].
35. Hardman S, Chandan A, Tal G and Turrentine T, The effectiveness of financial purchase incentives for battery electric vehicles – a review of the evidence. *Renew Sustain Energy Rev* **80**:1100–1111 (2017).
36. Hall D and Lutsey N, *Emerging Best Practices for Electric Vehicle Charging Infrastructure*. International Council on Clean Transportation, Washington, DC (2017).
37. Haugneland P, Lorentzen E, Bu C and Hauge E, Put a price on carbon to fund EV incentives – Norwegian EV policy success. EVS30 Symposium, Stuttgart (2017).
38. Runkel M, Mahler A, Ludewig D and Rückes AL, *Loss of Revenues in Passenger Car Taxation due to Incorrect CO_2 Values in 11 EU States* (2018), Available: http://www.foes.de/pdf/2018-03-10_FOES_Taxation_loss_due_incorrect_CO2_values.pdf [accessed 1 April 2019].
39. ACEA, *Electric Vehicles: Tax Benefits & Incentives in the EU*. ACEA, Brussels (2019).
40. Runkel M and Mahler A, *Fair & Low Carbon Vehicle Taxation in Europe: A Comparison of CO_2-Based Car Taxation in EU-28, Norway and Switzerland*. Forum Ökologisch-Soziale Marktwirtschaft (FÖS)/Green Budget Germany (GBG) (2018).
41. Tietge U, Mock P, Lutsey N and Campestrini A, *Comparison of Leading Electric Vehicle Policy and Deployment in Europe. White Paper*. International Council on Clean Transportation, Washington, DC (2016).
42. Hauff K, Pfahl S and Degenkolb R, Taxation of electric vehicles in Europe: a ethodology for comparison. *World Electr Vehicle J* **9**:30 (2018).
43. Chandra A, Gulati S and Kandlikar M, Green drivers or free riders? An analysis of tax rebates for hybrid vehicles. *J Environ Econ Manag* **60**:78–93 (2010).
44. Figenbaum E and Kobenstvedt M, *Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle Users: Results from a Survey of Vehicle Owners*. TØI Report 1492/2016. Institute of Transport Economics (TØI), Oslo, Norway (2016).
45. McDonald A and Schrattenholzer L, Learning curves and technology assessment. *Int J Technol Manage* **23**(7/8):718-745 (2002).
46. Wene CO, *Experience Curves for Energy Technology Policy*. International Energy Agency, OECD/IEA (2000).
47. McDonald A and Schrattenholzer L. Learning rates for energy technologies. *Energy Policy* **29**(4):255–261 (2001).
48. Kobos PH, Erickson JD and Drennen TE, Technological learning and renewable energy costs: implications for US renewable energy policy. *Energy Policy* **34**:1645–1658 (2006).
49. Ajanovic A and Haas R, Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy* **123**:280–288 (2018).
50. IEA. *Energy Prices and Taxes for OECD Countries*. IEA, Paris (2019).

Amela Ajanovic, PD, DI,

Dr Amela Ajanovic is a lecturer and senior research scientist at Energy Economics Group at Vienna University of Technology. She holds a master's degree in electrical engineering and a PhD in energy economics at Vienna University of Technology. She has more than 15 years of experience in the area of energy economics with a focus on sustainable transport. Her main research interests are alternative fuels and alternative automotive technologies, energy and transport policies as well as transition to a sustainable energy system and long-term energy scenarios. She has been involved in several national and international research projects related to these topics. She has authored more than 50 papers and journal articles.

Reinhard Haas, PhD,

Dr Reinhard Haas is a university professor of energy economics at Vienna University of Technology in Austria. He teaches energy economics, regulation and competition in energy markets, and energy modeling. His current research focus is on (i) evaluation and modeling of dissemination strategies for renewables; (ii) modeling paths toward sustainable energy systems; (iii) liberalization versus regulation of energy markets; (iv) energy policy strategies. He has been working in these fields since more than 20 years and has published more than 60 papers in reviewed international journals. Moreover, he has coordinated, and coordinates, projects for Austrian institutions as well as the European Commission and the International Energy Agency.

Greenhouse Gas Sci Technol. **0**:1–14 (2020); DOI: 10.1002/ghg.1985