

The environmental and financial implications of expanding the use of electric cars - A Case study of Scotland

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ABSTRACT

This paper investigates the expansion of electric cars and their impact on the environment and the user; assuming a future scenario where all of the light-duty vehicles that use an internal combustion engine will be replaced by electric cars in Scotland. The idea is to investigate the impact on the environment and the financial effect on the user. The methodology is based on analysing the most common electric and conventional vehicles to estimate the amount of additional electricity that would be needed to charge that expansion. The paper has also looked at the running costs. The results show that approximately 4 GWh per annum of additional electricity will be needed to compensate for such growth in electricity demand. With the rise in electricity production, the amount of carbon emissions from the electrical grid is expected to increase slightly by 0.47 megatons CO₂ per annum. Given that the carbon dioxide generated by the light internal combustion vehicles at the moment is 3.6 megatons of CO₂ per year, it is concluded that the total amount of greenhouse gases from the electricity grid will decrease by circa 33.7% if all conventional cars in Scotland are replaced by electric cars. The initial cost of an electric car is found to be higher than conventional diesel or petrol one, but in the long term, the cost to power an electric vehicle is expected to be much cheaper. However, electric cars still have their own drawbacks as they need significant time to be charged, and will consume significant energy for heating the interior and windscreens to prevent condensation in cold weather leading to an estimated reduction in range of approximately 28% in some situations.

1. Introduction

The world population has been increasing dramatically over the past few decades. With the growing population comes an increase in the number of vehicles and therefore the growth of greenhouse gases released from traffic. To mitigate that challenge, scientists and engineers are continuously working to improve conventional vehicles to enhance their performance of using less fuel and hence releasing fewer greenhouse gases to the atmosphere. Another solution on the horizon, and expanding rapidly, is the development of electric cars. Electric vehicles do not release any emissions, they require electricity to run and are considered by many as an eco-friendly solution for the ever-growing demand for more vehicles and more fuel. It is also a way to resolve the growing greenhouse gas and pollution levels in the atmosphere released from traffic. Other alternatives to conventional vehicles are hybrid cars and hydrogen fuel cell vehicles.

It has been estimated that the global social cost for air pollution associated with combustion engines is about 3 trillion dollars per year [1].

The increase in carbon emission not only contributes to poor air quality, but also to an increase in global temperatures; which influences the climate. In 2016, a new record has been set regarding the increase of global temperatures, which led to about 1 °Celsius rise compared to the 20th-century average temperature [2]. The Paris Agreement on Climate change provides the possibility for each country in the world to move forward in decreasing its greenhouse gas levels towards enhancing air quality. Investigating the reduction in greenhouse gas emissions by electrifying transportation is essential, as more than 55 countries emit more than half of the global emissions [1].

The availability of fossil fuel, particularly oil, is not sustainable; hence integrating electric cars and enhancing the use of renewable energy would extend the time of oil's availability, allowing other types of transport such as airplanes and ships to utilise the available resources. Moreover, the batteries of electric vehicles can be exploited as an additional grid storage reserve, where excess renewable energy can be stored and balance the variation in electricity demand. These reserves could also be utilised in emergencies or during unforeseen blackouts [3].

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A notable advantage that electric cars possess is their high efficiency in energy use. They also produce zero emissions at point of use, which contributes to considerable reduction of greenhouse gas emission from the transportation sector [4].

Despite the advantage of electric cars, widespread implantation of a fleet that consists mainly of EVs would lead to some challenges regarding the grid electricity generation system. Charging a high number of cars during peak hours could cause a considerable increase in electricity demand, leading to a significant overloading on the grid. A possible solution for that would be an adaptation of smart grid technology and demand management into the grid's infrastructure. This can be achieved by scheduling the charging processes accordingly with priority policies by recognising the vehicles with higher urgency of recharging. This would aid in flattening the demand curve and hence avoiding overloading the grid. Then, it is important to determine an appropriate charging rate (i.e. power consumption) for all electric cars that are connected to the grid [4].

The 2009 Climate Change Act for Scotland sets a target to decrease greenhouse gas emissions by 2050 to 80% compared to the emission levels in 1990. Five major steps were identified to achieve such goals [5]. These steps involve the reduction of fossil fuel usage and promoting the implementation of more renewable energy, which would help in reducing greenhouse gas levels. By 2016, Scotland has managed to introduce carbon capture and storage technologies. Also, the reduction of 12% in electricity demand has already been achieved. In addition, the country has closed the last operational coal power station shifting the electricity production to nuclear and renewables [5].

Even in places where the main source of electricity to charge electric cars is from fossil fuel, this would still have a positive impact on the environment. In an experimental case study to charge electric cars in Italy using electricity from fossil fuel, the amount of carbon emissions did not exceed the EU traffic limits of 100 g/km [6].

Some of the disadvantages of electric cars are the long charging times of the batteries, the relative short range of vehicles, and the high initial cost. The running cost of electric cars is considered to be lower compared to internal combustion engine cars, due to lower taxes the price difference between electricity and fossil fuel [7].

This paper suggests a novel approach which investigates a scenario where all conventional light-duty vehicles to be replaced by electric cars in Scotland. Vehicles and energy-related data from the years 2015–2016 is chosen for this paper's analysis. In order to properly investigate the situation, a literature review has been conducted regarding the electricity consumption in Scotland. Greenhouse gas emissions from energy generation and traffic pollution assuming the most popular cars among the gasoline/diesel and the electric technologies are estimated. The assessment of carbon emission when expanding renewable energy generation is also investigated. The paper also highlights a novel mathematical modelling and the implementation of infrared thermography to estimate energy losses in winter for electric cars and the effect on their travel range.

1.1. Brief description of conventional and electric vehicles

The amount of emissions released by conventional vehicles depends on the car's condition and how it is used. Those types of vehicles burn fuel to produce the energy which powers the engine. The fuel is drawn from the tank into one of the engine's cylinders. Each of the cylinders draws petrol/diesel in sequences together with the necessary quantity of air. The sparks, or pressure in case of diesel engines, ignite the mixture of fuel and air resulting in sudden expansion in volume within the engine's pistons causing them to move to produce the necessary motion. This motion from the pistons causes the driveshaft to be turned. The driveshaft then moves the axles via the gearbox, and as a consequence of that, the wheels of the car will rotate, producing the car's movement. The burnt fuel creates exhaust gases that are emitted into the atmosphere [8]. In 1870, the first internal combustion engine powered by

Table 1
Sources of electricity in Scotland and their Carbon Factor reproduced based on data from reference [16].

Source of electricity	Carbon Factor (gCO ₂ /kWh)
Nuclear	26
Coal	220
Gas	170
Hydro	7
Renewable	41.25

gasoline (petrol) was invented [9]. On the other hand, electric vehicles do not require chemical fuel. They require electricity to charge their batteries. The energy stored in the battery is utilised to power one or more electric motors via a controller. The electric motor is responsible for driving the vehicle's wheels. Some models have two motors placed on each axle of the car. Since electric vehicles do not use fossil fuels to be powered, they do not produce any emissions [10]. It is well known that at the end of the 19th century, electric cars were very common due to the simplicity of the technology. It has been observed that in 1899, 90 percent of taxi cabs in New York were electric [11]. Electric Vehicles (EVs) are considered to aid in reducing the levels of greenhouse gas emissions, particularly on busy roads. Oil as a resource is limited, and integrating electric cars will reduce the consumption of petroleum, increasing the time for its depletion and allowing other modes of transport, such as air and water to rely on oil. It has been suggested that the batteries on electric vehicles can be exploited as an additional grid storage system to store excess electrical energy to balance supply and demand [12]. Even though electric vehicles are eco-friendly, there are some challenges. One of them is the battery's low capacity, as well as its high cost. The small number of charging stations also poses a challenge at the moment. If more people start to use electric cars, the electricity demand from power stations will rise, hence contributing to greenhouse gas emissions unless more renewable or green energy resources are developed to replace coal, oil, and gas.

1.2. Electricity and carbon emission in Scotland

According to surveys in the monitoring of greenhouse gas (GHG) levels by the Scottish Government [13], about 20% of the greenhouse emissions are from conventional cars. Approximately 97% of the greenhouse gases are represented by carbon dioxide and a small amount by nitrous oxides, methane, and fluorinated gases [13].

Annually the electricity consumption in Scotland is approximately 38,000 GWh. The country produces on average 50,000 GWh of electricity and the amount that is not consumed locally is exported to England and Northern Ireland [14]. Fig. 1 presents the electricity generated, by source, between 2000 and 2016 and Fig. 2 shows the energy mix in Scotland in 2015–2016.

It has to be mentioned that when electricity is generated and distributed, there are losses through the grid, and Scotland is not an exception; the losses of the grid for the country are estimated to be approximately 17% [15].

Each source of electricity emits a different amount of carbon dioxide per unit of energy produced. The term used to describe this carbon footprint of the source of electricity is called the Carbon Factor. The unit of carbon factor is gCO₂/kWh. Table 1 presents the Carbon Factor for each energy source.

Taking into consideration the generation mix for the period 2015–2016, the carbon emissions from the electricity generation are estimated to be approximately 5 MtCO₂/year [14]. Depending on the generation mix, the number of emissions would vary. A high number of countries are focusing on building new nuclear power stations and utilising more renewable resources to reduce carbon emission and air pollution.

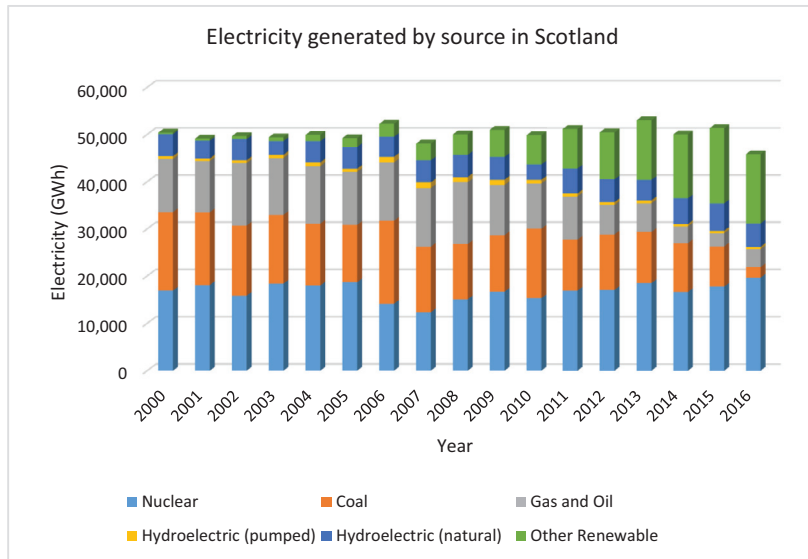


Fig. 1. Electricity produced by source between 2000 and 2016, figure reproduced based on data from reference [14].

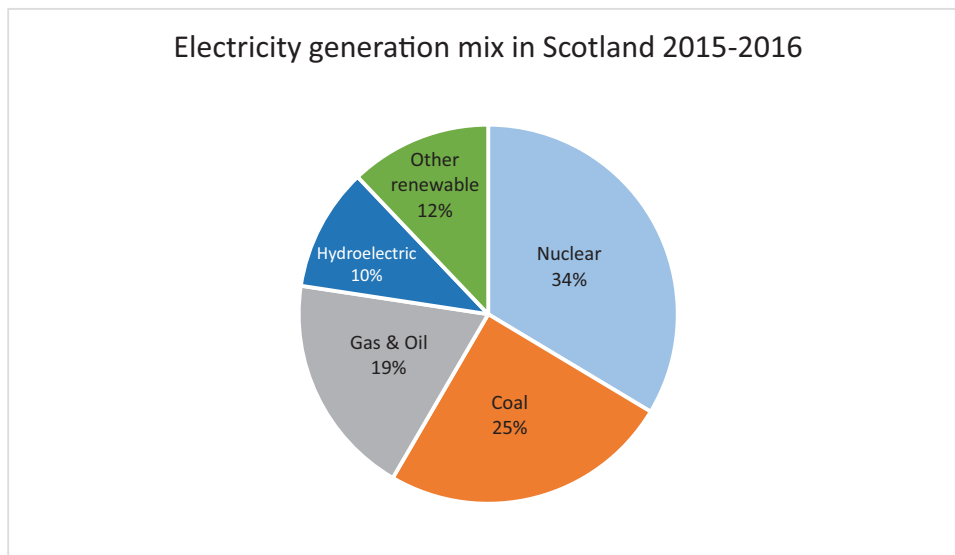


Fig. 2. Electricity generation mix of Scotland (2015), figure reproduced based on data from reference [14].

1.3. Traffic levels in Scotland

The average mileage per year of a vehicle in Scotland for the period 2015 – 2016 was roughly 11,362 km [17]. The number of vehicles in the Scottish fleet for the same period was estimated to be approximately 2240,000 [17]. According to data from Scottish traffic monitoring, approximately 80% of the fleet consists of light-duty vehicles [18]. According to this, it was estimated that light-duty cars produce roughly 3.6 Mt Carbon emissions per year [14].

Preferable car brands play an important role in the number of released greenhouse gases. Every conventional vehicle brand releases a different amount of carbon emission, and every electric car consumes a different amount of electricity, therefore, the emission from the electricity generation will vary. Research in the electric vehicles market in 2015 for the UK has revealed that among the most popular cars in this category were Nissan Leaf, BMW i3, Renault Zoe, Volkswagen e-UP, and Tesla Model S. Table 2 presents the top 5 registered electric and their specifications [19].

The same research has also been done for conventional light-duty cars, alongside their specifications, as shown in Table 3.

When comparing between winter and summer, the wasted heat from the internal consumption engine can be utilised to heat the passenger’s

compartment and prevent condensation on the windscreens. However, electric cars will need to consume energy from the battery to provide thermal comfort for passengers during cold weather. And the faster the car, the more are the heat losses, hence reducing the range of the electric car [21]. The winter in Scotland tends to be consistent with very little variations in temperatures with an average minimum winter temperature of approximately 1 °C [22], see Fig. 3. This is expected to reduce the electric vehicles’ range in winter.

1.4. Economics

From an economic perspective, the end-user is affected differently. The amount of money that a car driver is spending annually varies, depending on the type of vehicle, driven distance and driving conditions. Conventional cars require fuel whereas electric ones need electricity. The price of electricity and fuel is significantly different. The price of electricity and fuel varies depending on economic conditions. For the period between 2015 and 2016, that price was estimated to be around 12 pence per kWh of electricity [23]. For the same period, the price of a litre of fuel in the UK was approximately £1.3 [24]. Because Electric vehicles, plug-in EVs in particular, produce less than 50 gCO₂/km are considered emission-less [25]. For that reason, they are eligible to re-

Table 2
Top 5 registered electric vehicles in the UK for 2015, reproduced based on data from reference [19].

Brand	Battery capacity (kWh)	Consumption (kWh/100 km)	Number of registered cars in 2015	Price (£)	Distribution (%)
Nissan Leaf	24	14	11,000	29,000	49
BMW i3	22	13	3574	38,000	16
Renault Zoe	22	11	3327	21,000	15
Volkswagen e-UP	18.7	14	2500	19,000	11
Tesla Model S	85	16.9	2000	75,000	9

Table 3
Top 5 registered conventional vehicles in the UK for 2015, their CO₂ factor, price, Distribution, and average fuel consumption, reproduced based on data from reference [20].

Vehicle model	CO ₂ (g/km)	Price (£)	Distribution (%)	Number of registered cars	Consumption (L/100 km)
Ford Fiesta	147	15,400	30	133,434	4
Vauxhall Corsa	129	10,800	21	92,077	4.7
Ford Focus	159	18,000	19	83,816	3.7
Volkswagen Golf	112	20,600	16	73,409	3.9
Nissan Qashqai	162	19,800	14	60,814	4

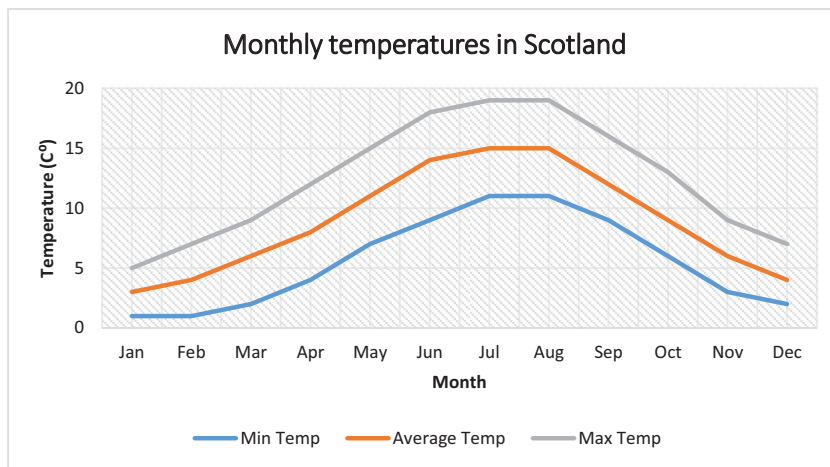


Fig. 3. The average monthly temperatures in Scotland reproduced based on data from reference [22].

ceive a 35% grant from the price of the electric car as a subsidy, which in most cases is reduced from the price of the vehicle. The maximum amount of that subsidy is £3500 [25].

1.5. Aim

This paper aims to determine what would be the impact on electricity demand, carbon emission and running and ownership costs, in a proposed scenario where fossil fuel light-duty vehicles are replaced with electric ones in Scotland.

2. Methodology

In order to find out what the effect of switching to electric cars would be, the methodology is divided into three parts: energy demand, carbon emissions, and costs.

2.1. Energy demand

The literature review has provided information on how much electricity is produced in Scotland annually and how much is the demand in a year. The number of light-duty cars is presented for the period 2015 – 2016. The first step of the methodology is to determine the increase in demand for electricity when moving from fossil fuel to electricity. In order to acquire an appropriate number, it has been found important to discover what are the most popular electric cars for Scotland,

Eq. (1) is utilised to determine the average value of electricity consumption among the most popular electric cars based on the market share for each brand and its specifications. The equation is as follows:

$$EC_{total} = \sum_{i=1}^n (EC_i \times PP_i) \tag{Eq. (1)}$$

Where *EC* represents the Electricity consumption (kWh/100 km) and *PP* is the Percentage Proportion of the vehicles according to the brand's popularity, represented as (value)% per 100; *n* is the number of cars included in the investigation.

Knowing how much is the annual mileage done by a car and how much is the average energy consumption of electric cars, the energy demand of a single car can be determined as:

$$RE = (ADT \div 100) \times AEC \tag{Eq. (2)}$$

Where, *RE* represents the Required Electricity for a single electric car (kWh), *ADT* is the Annual Distance Travelled (km), and *AEC* is the Average Electricity Consumption of an electric car (kWh/100 km). After determining *RE*, it is multiplied by the number of light-duty vehicles (2240,000). Through the literature review, the losses through the electricity grid have been established to be 17% which will be lost from the total electricity generated, hence 17% additional energy will need to be generated to compensate for that.

Determining the required variables, Eq. (2) will determine how much electricity a single car on average would need. By multiplying that value by the number of light-duty cars in Scotland, the annual electricity required to power all the electric vehicles for a year can be determined.



Fig. 4. The infrared image of the tested car during winter with calibrated temperatures based on the measured values from the temperature data logger.

It has been found also important to include the grid losses, which will give a more accurate value of the required future energy. Both current and future scenarios of electricity generation will be compared in this paper.

2.2. Heating of car's passenger compartment

Electric Vehicles will need to consume some of the power from the battery for heating the passengers' compartment. Hence, heating will affect electricity consumption and the available range. When considering the average interior space volume of light-duty vehicles, it has been estimated to be 2.93 m^3 [26]. Assuming the internal temperature is kept at $21 \text{ }^\circ\text{C}$ as the desired temperature, the minimum average ambient temperature in Scotland during the winter season is estimated to be $1 \text{ }^\circ\text{C}$ [22]. The following equation hence can be used to determine the heat required to warm up the car's interior:

$$E = m \times c \times (T_d - T_c) \quad (\text{Eq. (3)})$$

Where: E is the energy required to reach the desired temperature T_c ; m is the mass of air inside the car; c is the specific heat capacity of the air inside the car in $\text{J/kg} \cdot ^\circ\text{C}$; and T_d is the desired temperature in $^\circ\text{C}$.

Before applying Eq. (3), the mass of air (m) is determined using the following calculation:

$$m = \rho \times V \quad (\text{Eq. (4)})$$

Where ρ is the density of the air in kg/m^3 ; and V is the volume of the car's interior space volume in m^3 .

The heat losses through the windows and external envelop are calculated using Eq. (5) [27]:

$$P = 5.67 \times \epsilon_{hot} \times \left[\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_{out}}{100} \right)^4 \right] + 3.8054 \times \vartheta \times (T_i - T_{out}) \quad (\text{Eq. (5)})$$

Where: P is the thermal power loss through convection and radiation in W/m^2 ; ϵ_{hot} is the emissivity which for glass is 0.93 [28] and for iron/aluminium is 0.29 [28]; T_i is the surface temperature in K; T_{out} is the ambient temperature in K; 3.8054 is the convection heat transfer coefficient in $\text{W/m}^2 \cdot \text{K}$; ϑ is the wind speed in m/s . For ϑ the speed of a car is chosen to be on 60 miles/h or 97 km/h, which is in SI units will be 27 m/s .

In order to determine T_i for the windows' surface and the car's body surface properly, a thermal image of a vehicle is taken and a temperature data logger was attached to the external body of the car to evaluate the temperature performance. The car was driven at 60 miles per hour and

the external surface temperature of the car was measured. Fig. 4 presents the infrared image of the car, with calibrated temperature readings. The results have indicated that T_i for the windows was $9.9 \text{ }^\circ\text{C}$ and the vehicle's body surface was $5.5 \text{ }^\circ\text{C}$. The authors have used a diesel engine car to estimate the windows and body temperature when the internal compartment is at $21 \text{ }^\circ\text{C}$. The assumption is that an electric car will need to maintain the same internal temperature from the batteries for a similar journey and weather conditions.

Eq. (5) is used for the total windows and windscreens area which is estimated to be at a temperature of $9.9 \text{ }^\circ\text{C}$ and an area of 2.96 m^2 ; and also for the car body (doors and panels) which is estimated to have an area of 5.57 m^2 [29] and at a temperature of $5.5 \text{ }^\circ\text{C}$. Eq. (4) is used to calculate the energy needed to keep the passengers' compartment at a temperature of $21 \text{ }^\circ\text{C}$ with the assumption that the driver is the only person on-board without other passengers. This analysis will provide the amount of energy that will be needed from the battery to keep the driver at a comfortable temperature and prevent condensation on the windscreen (ignoring any electric heaters used directly to heat the windscreen). This is expected to influence the actual range of the car in cold weather and the analysis will provide an insight into this. The average range of an electric car is calculated using Eq. (1) to determine the average battery capacity and Eq. (2) to find out the average range of an EV. Eq. (2) is used to calculate the range when the heating is needed and to compare the range in warm weather when heating is not needed but ignoring air conditioning systems for cooling). The analysis assumed the driver's body will produce 100 W of heat while in the car.

2.3. Carbon emission

The literature review has provided useful information on how much carbon emission light-duty vehicles produce and the carbon factor of each source of electricity in Scotland for the period of 2015–2016, and the information needed on how much electricity Scotland produces per annum and the carbon factor of each source. The carbon emission level can be calculated for each energy source using Eq. (6):

$$CE = AE \times CF \quad (\text{Eq. (6)})$$

Where CE is the Carbon Dioxide Emission from the electricity production in kg; AE is the amount of electricity in kWh; and CF is the carbon factor of the source of energy in kgCO_2/kWh . To simplify the presentation of figures, the Carbon Emission values are presented in kilotons (kTons).

Following the calculation of the carbon emission from each source, the total carbon emission for each scenario is calculated taking into consideration the electricity generation mix by percentages and an estimated 17% of grid losses. Using the same methodology as above,

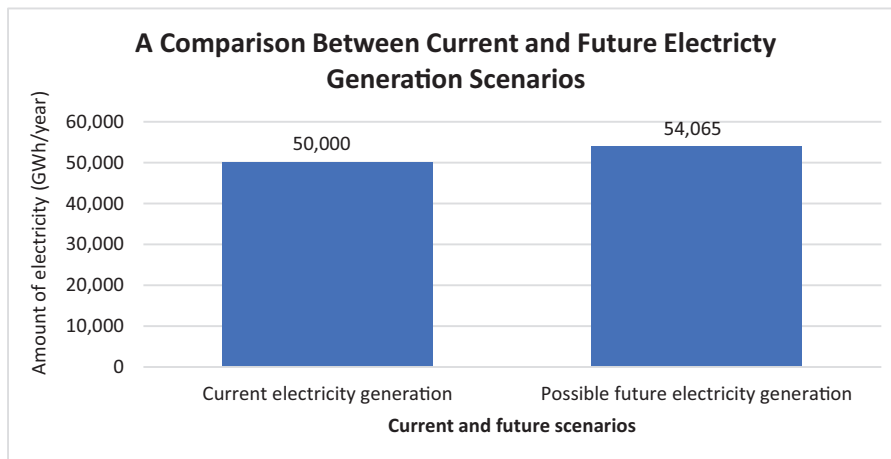


Fig. 5. A comparison between the current and future scenarios of electricity generation.

the amount of carbon emission from the additional energy generation needed for electric cars is calculated. Hence, the carbon emission level between the current time period (2015–2016) and the possible future scenario of electricity generation is considered. From the literature review, it has been found that the CO₂ emission from the current traffic is about 3.6 Megatons (MTons) per year.

2.4. Initial and running costs

It has been found essential to estimate the ownership and the running cost of electric cars in comparison to conventional technology. Eqs. (1) and (2) are utilised to determine the average fuel consumption among conventional cars in Scotland and how much fuel the total amount of light-duty vehicles in Scotland would need. Such values are needed in order to calculate the cost of fuel for a year per vehicle. Knowing consumption values and the price of fuel (£/L) and electricity (£/kWh), the cost of running an electric car versus a conventional car can be compared.

3. Results

3.1. Energy demand

Using Eq. (1), the average electricity consumption among popular electric cars in Scotland is calculated to be 13.65 kWh/100 km. This value is used in Eq. (2), which allowed us to determine the annual energy required for a single electric car, which is estimated to be 1551 kWh. By multiplying the required energy per vehicle to the number of light-duty vehicles on the road (2240,000 vehicles), the total energy required for all the electric cars in Scotland would be 3474,045,120 kWh, or simply 3474 GWh. The grid loss of 17% has been considered as well to get a more accurate value for the required energy that will need to be produced. Hence the total energy to be generated is 1.17×3474 GWh, making the minimum future energy generation to be 4065 GWh. Fig. 5 presents the electricity production needed in both scenarios.

3.2. Car heating

The power needed to heat the car's interior during the winter, including heat losses through windows and car's body surface; assuming a car speed of 60 miles per hour and the ambient temperature of 1 °C, is calculated to be 5.36 kW. Which when expressed in terms of range, this will be equivalent to a reduction in the range of about 28%, given the above-assumed conditions and that only the driver is on-board. Fig. 6 presents an example of the expected difference in the range of an electric vehicle during cold and warm seasons due to the power needed to heat the car's interior and windscreens in cold weather.

3.3. Carbon emissions

By applying Eq. (6), the carbon dioxide emission from the electricity generation produced from each source for the period of 2015–2016 and in the case of the future scenarios are presented in Table 4 and Fig. 8, which compare between five scenarios of carbon emissions of Scotland, as follows:

- The current scenario with the current energy mix (the current number of conventional cars).
- A future scenario of carbon dioxide emission, assuming the same current energy mix, for the additional electricity to charge the new electric cars.
- A future scenario of carbon dioxide emission with fixed current coal production levels but no further energy coal production for the additional energy.
- The assumed current scenario of carbon dioxide emission if the energy from coal is replaced by other sources as relative benchmark.
- A future scenario of carbon dioxide emission when no electricity is produced from coal and the rest of the energy mix maintains the same energy ratio.

Adding the additional amount of CO₂ emissions to the current scenario, (scenario a), reveals that the future carbon dioxide levels would be approximately 5503.3 kTons for the same energy mix (scenario b). It is expected that coal will be phased out either only for the additional energy produced for electric cars (scenario c); or completely eliminated (scenario e), where more renewable and nuclear energy will be utilised to generate electricity.

Scenario (d) is an assumed scenario for the current carbon emission from the electricity grid when coal is eliminated from the energy mix while maintaining the same ration of other energy sources. This suggests that carbon emissions from the grid will be reduced as renewable energy produce about 47.25 gCO₂/kWh, whereas coal is emitting approximately 220 gCO₂/kWh.

The resultant carbon emission and percentage of energy mix are presented in Fig. 7, where scenario (e) could be achieved by removing all coal from the mix, this should achieve a reduction in carbon dioxide emission of about $\frac{5089.50-3372.94}{5089.50} = 33.7\%$.

From Fig. 8, it can be concluded that the total amount of emissions from traffic and electricity production combined will decrease when electric cars are implemented in the Scottish fleet. This is an estimated decrease of approximately $\frac{27.2-24.1}{27.2} = 11.4\%$, this is the overall reduction from all sectors combined including residential, grid, transportation, industrial and agriculture.

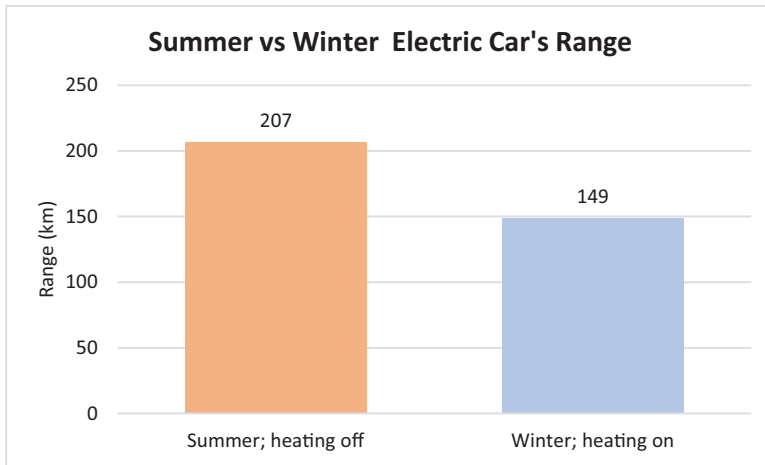


Fig. 6. A comparison between an EV during the summer and an EV during the winter with heating on.

Table 4
The amount of CO₂ emitted from the electricity generation produced from each source for current and future scenarios.

	Scenario (a) Current Emissions	Scenario (b) Future Emissions (assuming current% of energy mix)	Scenario (c) Future Emissions (with fixed coal production levels)	Scenario (d) Current Emission (assumed replacement of all coal energy sources)	Scenario (e) Future Emissions (no coal sources)
Source	Emissions per source (kTons CO₂/year)	Emissions per source (kTons CO₂/year)	Emissions per source (kTons CO₂/year)	Emissions per source (kTons CO₂/year)	Emissions per source (kTons CO₂/year)
Nuclear	442	447.94	489.91	589.33	637.25
Coal	2750	2973.59	2750	0	0
Gas	1615	1746.3	1790.07	2153.33	2328.4
Hydro	35	37.85	38.79	46.67	50.46
Renewables	247.5	267.62	274.33	330	356.83
TOTAL	5089.5	5503.3	5343.1	3119.33	3372.94

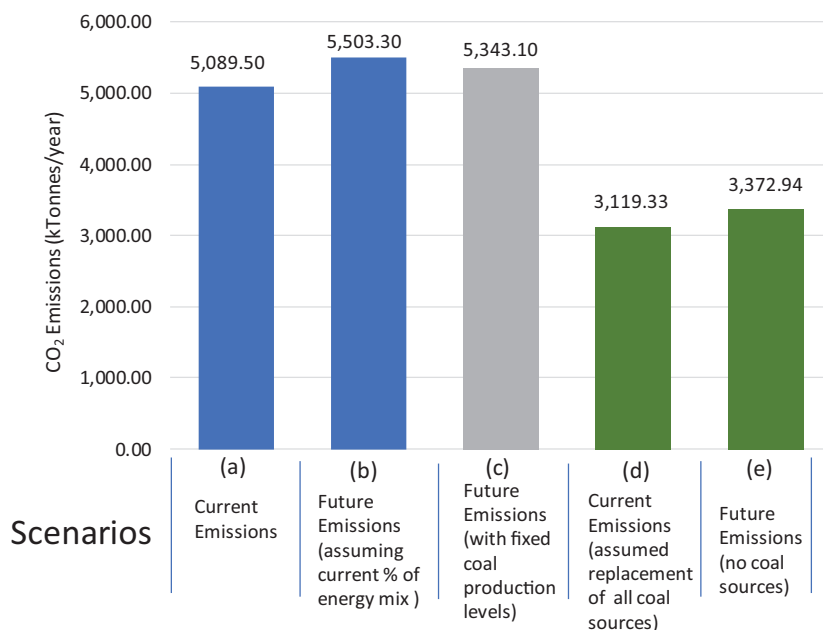


Fig. 7. A comparison between five scenarios of carbon dioxide emissions from electricity generation.

Annual Energy Generated (GWh)	50,000	54,065	54,065	50,000	54,065
% Coal	25	25	23.12	0	0
% Nuclear	34	34	34.85	45.33	45.33
% Gas	19	19	19.48	25.33	25.33
% Renewables	12	12	12.3	16	16
% Hydro	10	10	10.25	13.33	13.33

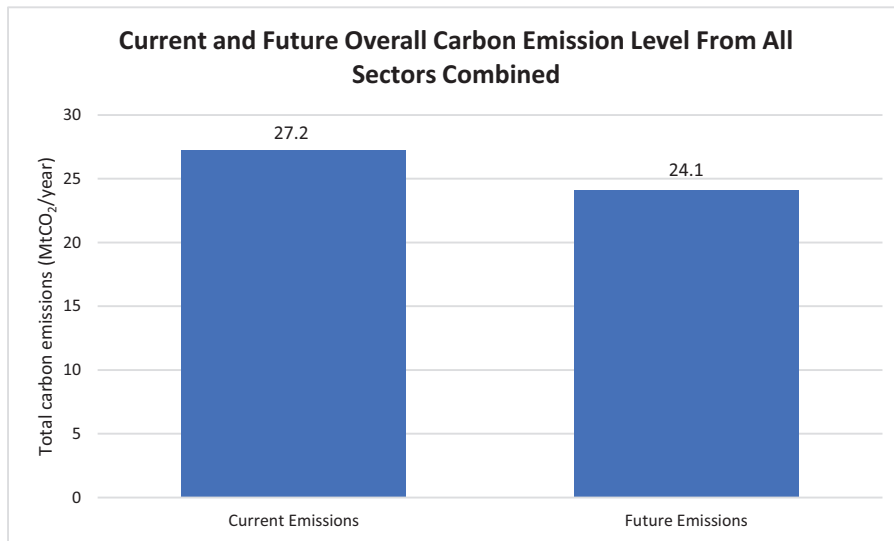


Fig. 8. A comparison between the current and future total carbon emission in Scotland from all sectors.

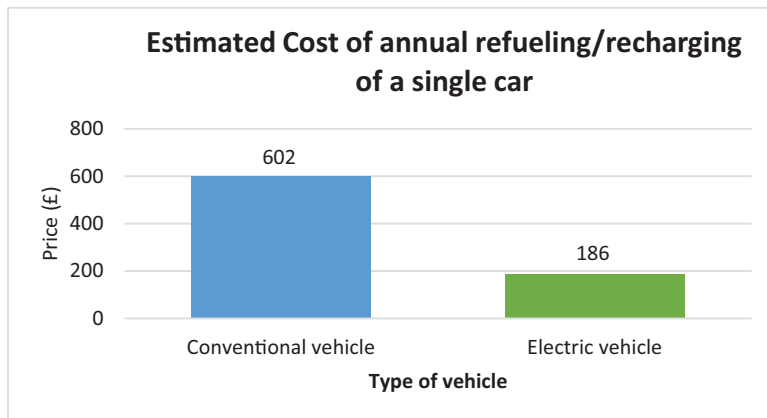


Fig. 9. A Comparison of refuelling/recharging cost for 1 year.

3.4. Estimated costs of ownership and use

The application of Eq. (1). Eq. (2) has revealed that a petrol/diesel car would need approximately 483 Litres of fuel in order to cover the expected annual mileage of 11,362 km per vehicle. For the same distance, an electric vehicle would need about 1551 kWh to cover the required distance per annum. Taking the price of fuel and electricity into consideration, the results are presented in Fig. 9 where the estimated running costs of a petrol/diesel fuel and electric vehicle are estimated to be £602 and £186 respectively. Hence, it is clear that electric cars are about 69.1% cheaper to be powered. In this analysis, maintenance costs are ignored for both types of vehicles.

Fig. 10 presents the initial ownership cost of both types of vehicles. Currently, it is estimated that electric cars are currently 97% more expensive than conventional ones without any subsidy.

Since the maximum subsidy of an electric vehicle that can be granted in the UK is £3500, Fig. 11 presents the overall cost indicating electric cars to be only 75.7% more expensive.

4. Discussion

This paper has looked at a case study scenario where every light-duty vehicle in Scotland is assumed to be replaced by an electric car. The investigation and the calculations are based on the popular brands and models of both types of vehicles for the period of 2015–2016. For popular cars, the number of registered ones in 2015 is considered. In the future, changes can be expected, because new and more efficient

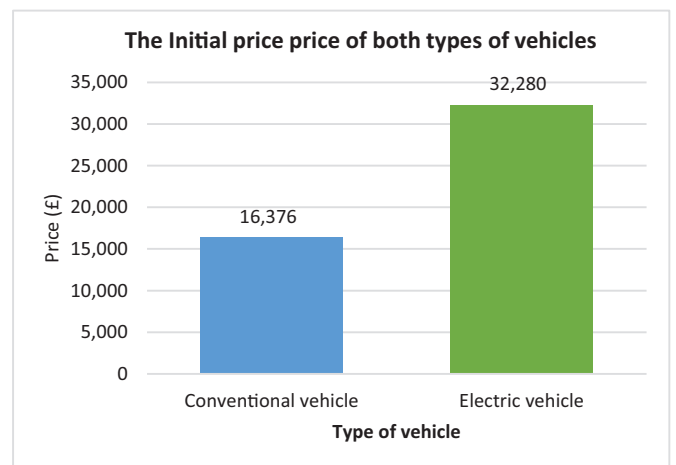


Fig. 10. The initial cost comparison between electric and conventional cars.

vehicles may appear in the market. Due to such expected changes, the prices of vehicles and fuel/electricity may vary through the years. Car models that have been considered new for that period will drop in price with time. The situation with the price of electricity and fuel is similar, their price varies slightly through the years. When the demand for electricity increases it is expected that its cost might rise as well. Since 2016 the prices of electricity from solar panels and wind turbines have

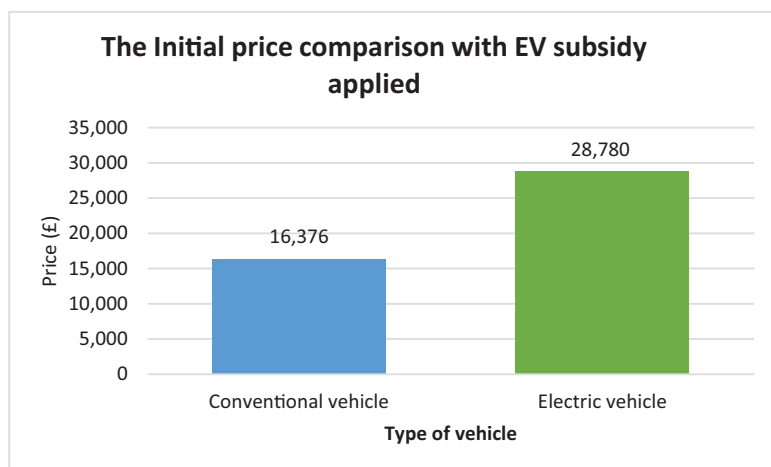


Fig. 11. Initial cost comparison between electric and conventional cars with EV subsidy applied.

significantly decreased. In fact, nowadays wind energy is considered to be the cheapest source for electricity production. According to Wind Europe [30], the cost of offshore wind is expected to decrease to €60 (£55)/MWh by 2025. Bloomberg New Energy Finance (BloombergNEF) also predicted that by 2022 the ownership cost of electric cars will decrease below the conventional diesel and petrol ones. In addition, the cost of lithium-ion batteries has dropped by 65% between 2010 and 2016 and it is expected that by 2030 the price of EV batteries will drop below \$120/kWh (circa £98/kWh) [31].

Regarding the economic point of view, this paper has not taken into consideration the maintenance cost of conventional and electric vehicles, more specifically the engine and battery life. Another important point excluded from this paper is the fact that Battery EV (Plug-in EV) owners are exempt from road tax [32]. From the economic perspective, another point which is not taken into consideration is the cost of the charging stations that owners may pay for. Those costs normally include a monthly fixed fee and a demand charge [33].

In March 2016, Longannet, the 2400 MW coal-fired power station was closed, leaving Scotland with very little energy generated from that source [34]. Since then the country distributed that demand across gas and wind energy. This has led to a more sustainable future which is discussed in this paper causing a positive prediction regarding carbon emissions from the energy generation sector. CO₂ levels are expected to be reduced over the coming years in Scotland. Hence, further research in the area will be required when more renewable energy is added to the grid [35]. As for the emissions in Scotland, only values from the traffic and the electricity generation are considered in this paper. The emission from the manufacturing of both types of cars is not considered in this paper. Research show that there are no significant difference in the carbon emission; however, electric cars require slightly more carbon to be manufactured due to the battery [36]. However, life-cycle assessment of both types of vehicles should be investigated further in order to acquire more accurate numbers on the long term, given the expected improvement of the technology of the battery.

The production of electric car batteries contributes to the generation of carbon emissions, which has not been taken into consideration in this paper. Conventional vehicles do not only contribute directly to CO₂ emissions by burning the fuel, but also indirectly by the extraction of oil, its process operations, and the transportation of gasoline/diesel to the gas stations, which all produce carbon emissions. That is not included in this investigation either. Moreover, the additional energy that will be needed for heating during cold seasons is not included in the analysis of energy demand for electric cars, and it will be the subject of futures studies due the variation in weather conditions. Further research is still required to explore further the effect of the electric cars on the environment, and their cost impact on the owners.

5. Conclusion

The scenario of replacing all diesel and petrol light-duty vehicles in Scotland with electric cars would have diverse pros and cons. As a result of the massive expansion of electric vehicles, the electricity demand will be expected to rise and hence the production of more energy leading to a slight increase in carbon emission levels. Although the CO₂ levels are expected to rise in such a situation, the traffic emissions will decrease significantly because there would not be any light-duty vehicles to pollute during operation. Therefore, this will lead to a reduction in the total amount of carbon emissions from the electricity grid by approximately 33.7%.

In addition, during cold weather, owners would need to use the electric heating of the car, which uses energy from the battery, this is expected to reduce the range by 28%.

With extended utilisation of electric vehicles, owners would spend more money as an initial cost compared to conventional cars (about 75.7%) even with the EV subsidy in the UK. In the long term, electric vehicles would save money to their owners, because of the considerably low price of electricity compared to that of petrol and diesel fuel, with estimated savings of about 69.1% per annum.

All in all, the extended usage of electric vehicles in such scenario is expected to have a positive impact on the environment. Although, it depends on what the electricity generation mix is. The more eco-friendly sources are used to generate electricity, such as renewables and nuclear power plants, the more the positive impact would be. One of the main advantages is reducing pollution on busy roads and in cities, which should contribute to better public health conditions.

Declaration of Competing Interest

The authors declare that there is no conflicts of interest.

CRediT authorship contribution statement

George Milev: Software, Validation, Writing - original draft, Visualization, Formal analysis, Conceptualization, Investigation. **Astley Hastings:** Supervision, Conceptualization, Methodology, Validation, Writing - review & editing. **Amin Al-Habaibeh:** Supervision, Conceptualization, Methodology, Investigation, Validation, Writing - review & editing, Visualization, Formal analysis.

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