Renewable and Sustainable Energy Reviews 174 (2023) 113160

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Pathways to decarbonising the transport sector: The impacts of electrifying taxi fleets

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ARTICLE INFO

Keywords:
Taxi
Electric vehicle
Emission modeling
Multi-criteria analysis
Scenario analysis
Net-zero target

ABSTRACT

The impacts of climate change have prompted governments to pledge to introduce policies aiming to limit the increasing temperature. One of the strategies involves reducing and, eventually, eliminating internal combustion engines in favour of electric vehicles. This strategy has been implemented by many transportation services, and FREE NOW has pledged to be carbon neutral by 2030. This study analyses the FREE NOW taxi fleet composition in Dublin in 2021 and investigates the reduction in emissions from fully electrifying the fleet. The analysis uses an emissions tool to model a combination of scenarios, consisting of different vehicle powertrain and fuel type configurations. An emission factor is applied to the EVs to calculate the emissions produced by the electricity used to power the vehicles. The results show a 77% decrease in carbon dioxide emissions from fully electrifying the fleet. Multi-criteria analysis is used to assess the strengths and weaknesses of each scenario developed. The S-5 scenario, consisting of the EVs only, scored the highest for many of the criteria. S-5 was identified as the best option for the taxi fleet, followed closely by S-4 involving an upgrade to all plug-in hybrid EVs. The S-4 scenario seems to be a good alternative when an EV is too expensive or access to charging infrastructure is not provided. The infrastructure currently available in Dublin will not accommodate the all-EV taxis target by 2030.

1. Introduction

Carbon neutrality has been at the centre of the progress of many technological advancements [1]. As rising temperatures have become a global issue, the aim of carbon neutrality has been agreed upon by many countries that have signed the Paris Agreement and pledged to attain a reduction in greenhouse gas (GHG) emissions by 2030 and neutrality by 2050. GHG emissions contribute to global warming [2], and are a major concern globally, and other pollutants emitted by the transportation sector cause severe health problems and death [3]. In 2016, it was estimated that 6.5 million deaths per year are attributed to contaminants in the air, which is more than tuberculosis, AIDS/HIV and accidents on the roads in total [4]. Many health problems have all been attributed to particulate matter (PM) [5]. Diesel engines are high producers of PM and nitrogen oxides (NO_x), whereas petrol engines produce more carbon dioxide (CO_2) emissions than diesel engines of a corresponding size. However, since larger displacement engines produce more CO_2 emissions, a small-engine petrol vehicle will emit less than a larger-engine diesel vehicle [6]. Policies have been put in place to reduce the emissions from the exhaust, i.e., the Euro Standards in Europe. These policies have placed limitations on the levels of specific pollutants that are expelled from petrol and diesel engines.

Technological development brought enormous improvements in electric engine technology and future advances will increase the popularity of electric vehicles (EVs). In comparison to the internal combustion engine (ICE) that has a fuel efficiency of 25%, the efficiency of an electric engine is 80% [7]. In one month it is possible for an EV taxi to save 1000 L of petrol and, in turn, the reduction of CO_2 emissions could be as much as 3200 kg [8]. EVs are particularly suitable for taxis due to the short length of trips and lower than ICEVs operational costs [9]. The costs are lower because of the higher energy efficiency of EVs, reduced maintenance cost with fewer moving parts to maintain, and electricity being less expensive than fossil fuels – this however depends on the country's fuel price to electricity ratio and taxation system. In urban settings, EVs present a direct means of reducing emissions as they do not

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https://doi.org/10.1016/j.rser.2023.113160
Received 20 August 2022; Received in revised form 3 January 2023; Accepted 3 January 2023
Available online 7 January 2023

Nomenclature

BAU	Business-as-usual
CO_2	Carbon dioxide
EV	Electric vehicle
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
LC	Life cycle
LCA	Life-cycle assessment
MCA	Multi-criteria analysis
NO_x	Nitrogen oxides
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
VOCs	Volatile organic compounds

have an exhaust. When considering the environmental impact of an EV versus an ICE vehicle (ICEV), the entire life cycle (LC) must be assessed. On the road, an EV produces no greenhouse gas (GHG) emissions, but when the means of accessing the electricity and batteries are considered, the environmental impact may be substantial [10].

Hybrid electric vehicles (HEVs) are propelled by fossil fuels and electricity. The running costs of these vehicles are low and the fuel efficiency is higher compared to ICEVs [7]. The hybrid powertrain has been more attractive to taxi drivers as it removes the need to charge the vehicle which takes away valuable time from the vehicle owner. As for plug-in hybrid electric vehicles (PHEVs), the time taken to charge the battery is a disadvantage. The battery capacity restricts the distance travelled on electric power, however, equipped with a combustion engine, a PHEV can switch to using petrol or diesel fuel [11]. The electric-driving range of PHEVs varies from 20 km to 100 km [12].

The introduction of EV taxis may be the solution to eliminating pollutants the ICEVs emit in the immediate future. The impact of an ICE taxi on air quality in urban areas is much higher compared to a private vehicle, because of longer daily travel distances and the idling time of taxis [13]. The annual kilometres driven by a taxi are greater than that of a private vehicle. For instance, in China, the taxi fleet is relatively small in comparison to private vehicles at 1% of the total vehicles in urban areas, but they account for more than 20% of the air contaminants and use of energy [8]. Replacing ICE taxis with electric ones will significantly reduce per-vehicle GHG emissions and multiple cities are already promoting electric taxis [11,13]. The governmental incentives have led to small increases in EV sales by 4.9% in China, 2.1% in the US and 3.5% in the EU, in 2019 [14], but in many countries, the demand has not risen as it was predicted. The main issue that has caused a lack of interest, especially in business models, is the limitation of the distance that can be travelled and the length of time it takes to charge the vehicle [15]. While the initial costs can be outweighed by the cheaper running costs and lower vehicle taxation, charging poses a major issue as it reduces the time that the vehicle can be on the road. Full electrification of taxi fleet requires efficient and fast charging infrastructure. Rapid charging infrastructure needs to be investigated as it is expected to accelerate electrification of the fleet and have positive impacts in urban areas through a reduction in air pollution [16].

Several studies were conducted to assess the viability of the implementation of this proposal and the costs and benefits of such. A case study was completed in New York City in the US by Hu et al. [11] to examine the viability of the replacement of ICE taxis with EVs. The travel patterns were examined for a fleet of taxis and from the trip data, ten variables were extracted for analysis. Hu et al. [11] concluded that the charger availability was insufficient and would not be able to sustain a large fleet of electric taxis. The study suggested that an extended availability of chargers could support half of the current taxi fleet. The waiting time for the charges would also be an issue for a taxi driver.

To predict the economic and environmental effects of taxi fleet electrification in South Korea, Kang and Lee [13] performed a cost-benefit analysis (CBA) of this proposal. The basis for the analysis is that the gradual phasing out of the current fleet of taxis can be achieved by 2026 allowing for a complete EV taxi fleet. The parameters considered for the CBA were the costs of purchasing the EVs and charging (i.e., infrastructure provided), and the benefits of a reduction in the operating costs and the overall improvements in the environment (i.e., air pollution and GHG emissions). They considered an appraisal period of 9 years and a discount rate of 5.5% [13]. The CBA showed that the improvements in air quality and GHG emissions would be positive. It was found that the fuel and maintenance savings resulted in a cost/benefit ratio of 2.20. This proved that the implementation of a gradually phased shift to EV taxis would produce positive results, both economically and environmentally [13].

A similar CBA was completed by Mingolla and Lu [9] for the electrification of a taxi fleet to fully analyse the reduction in the emissions of CO_2 and the overall costs that would be incurred over the period from 2021 to 2030. The baseline and gasoline fleets were found the highest producers of CO_2, followed closely by diesel vehicles. The more sustainable means of energy production used by the fuel cell electric vehicles produced the lowest emissions of CO_2, especially if used in conjunction with hydrogen produced from renewables [9]. The optimum choice of vehicle is based on the price of hydrogen and the carbon intensity of electricity production. The study concluded that the distance travelled by the taxis affects the ranking of the vehicle in relation to the reduction of cost.

Ara Aksoy et al. [17] completed an analysis using four scenarios to determine the effectiveness of introducing strict government policies on lowering the negative health impacts and death rates in Turkey. The study found that the harsher countrywide policies and the introduction of EVs and HEVs would result in a drop in deaths of between 9241 and 19,396 over the ten-year period from 2020 to 2030. The benefits in this analysis outweighed the costs in relation to the lives saved. This study focuses on the electrification of the FREE NOW taxi fleet in Dublin. The city is the capital of Ireland with 40% of the country's population living in its metropolitan area. It is estimated that in 2019, half of the people travelling to and from the city centre used public transport modes. Although only 1.2% of people move around using a taxi service, taxis accounted for 8.5% of all cars crossing the canal cordon in the same year [18]. In line with a target of the transportation sector in Ireland to reduce overall emissions by 51% by 2030, local authorities continue to restrict private vehicles and parking spaces in city areas, which is expected to increase the demand for public and shared transport, including taxi services. As demand for eco-travel options grows so do the aspirations of service providers. FREE NOW has "pledged to be the first mobility platform in Europe to reach Net-Zero emissions by 2030" [19]. The total number of valid taxi licence holders in Ireland as of the March 31, 2022 was 25,369 [20], with the majority of these licence holders in the Greater Dublin Area. The taxi fleet in Dublin is 1.5 times the size of the taxi fleet in the rest of the country. It follows that the fleet produces 1.5 times more emissions. Each taxi in the fleet produces approximately 2.5 times the amount of air pollution as a private car [21]. The current fleet of taxis in Dublin is represented by a mixture of vehicle types and fuel types. The electrification of this fleet requires analysis to fully understand the implications in relation to emissions. The overarching aim of this research is the quantification of the annual emissions produced by the FREE NOW taxi fleet in Dublin, Ireland, for the year 2021 and the impact that converting the fleet to EVs would have on emissions. In line with this, the main objectives of this study are.

- To model the FREE NOW taxi fleet in 2021 using COPERT and assess the level of annual emissions produced by the fleet, including GHG and non-GHG emissions;

- To design scenarios representing the gradual phasing out of ICEVs towards an all-electric fleet and calculate the annual emissions produced by each scenario in COPERT;
- To quantify the emissions produced by the EVs based on the source of electricity used to power the vehicle;
- To complete a CBA to compare the capital costs in comparison to the emission costs for each scenario using the Common Appraisal Framework [22];
- To compare each scenario using multi-criteria analysis (MCA) consisting of criteria: economic impacts, safety impacts, environmental impacts, accessibility, impact on a vehicle owner, and infrastructure requirements;
- To reach a conclusion on the implications of converting the current FREE NOW taxi fleet to a fully electric fleet.

2. Material and methods

This study is based on the data provided by FREE NOW concerning their taxi fleet in 2021. The data is used to model the fleet using COPERT which calculates the emissions produced by the fleet. The emissions that are being considered in this research are exhaust GHG and non-GHG emissions. The benefits from emission reduction were contrasted with the costs for the exchequer in CBA. The five scenarios are designed to investigate the phasing out of ICEVs with the baseline scenario being business-as-usual (BAU). The scenarios were compared on a point scaling system using the MCA.

2.1. Data for emission model

To populate the COPERT model, the following data required for the COPERT analysis were collected: environmental data, trip characteristics, stock configuration, and circulation data. This data was compiled from various sources referenced below. FREE NOW provided the stock configuration and average trip duration of the Dublin taxi fleet for the year 2021.

The environmental data comprising mean, minimum and maximum temperatures and relative humidity were obtained from Met Eireann [23] and are presented in Table A-1.

The data on trip characteristics provided by FREE NOW contains the average trip duration from which the average trip length was calculated. The average trip duration is 0.27 h and the distance travelled during a single trip is estimated to be 8 km under the assumption of a 30 kph average speed. The annual average taxi travel distance is between 42,000 km and 49,000 km [21], and a mean of 45,500 km was used for the analysis. The emissions due to idling were not considered as no data was available.

The sample of data provided by FREE NOW contains 10,050 vehicles, described by counts of the make, model of each taxi in the fleet, and fuel type. There were 456 EVs in the stock and these were excluded from the COPERT analysis as they do not emit combustion gases. The 456 vehicles was used for post-COPERT analysis, however the count constantly increases and as of August 2022 the fleet consisted of 750 EVs. The remaining 9594 vehicles in the taxi fleet are a combination of petrol/diesel hybrids and ICEVs. To compile the stock configuration the engine type and the euro classification are required. A combination of assumptions was made for the cases where the make and model spanned several decades and a Euro Standard could not be definitively applied. The assumptions consider information on the registration year of the vehicle (Table A-2), the age range of the current taxi fleet in Dublin (Table A-3) and the assumption that the fleet does not consist of older than 15-year vehicles given a high insurance cost for such vehicles [24]. When the information on fuel type was not provided, the percentages of each engine type in the fleet were used to fill in missing data (Table A-4). The stock configuration includes petrol PHEVs, diesel PHEVs, petrol HEVs, and petrol and diesel ICEVs, including minivans and multipurpose vehicles (Table A-5).

The circulation data required by the COPERT model is the speed and the mileage share. The speed is based on the limits set out by the government [25]. The speed limits in Dublin range from 30 kph to 50 kph, and the lower value of 30 kph was applied for urban traffic (peak and off-peak). A speed value of 80 kph was considered for rural, and 120 kph for highway traffic. The mileage share was assumed to be 70% (50% peak, 50% off-peak) for urban trips, 15% for rural, and 15% for highways [26].

2.2. Emission estimation method

The COPERT model was used for estimating exhaust GHG emissions and non-GHG emissions produced by the FREE NOW taxi fleet in Dublin in 2021. Among species considered by COPERT, carbon dioxide (CO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) were selected for analysis in this paper. The non-exhaust emissions, such as PM, were excluded from the analysis as we do not expect that their amount would differ substantially between the vehicle categories [27]. While the authors acknowledge that other air pollutants could have been measured using the emissions model it was decided to limit it to the species that are monetized and measured by the Irish Department of Transport [22].

Emission models can be classified into static and dynamic. Within static models, two categories are distinguished, average speed emission and aggregated emission factor models [28]. The COPERT falls into an average speed models group and is a recognized tool for preparing inventories of road transport emissions in Europe [29]. COPERT along with the MOVES model, and its previous version, MOBILE, are the most commonly used methods to estimate emissions from mobile sources. The latter two models use a single emission factor for a wide range of vehicles [30]. In contrast to COPERT, emissions are calculated based on fuel quantity and vehicle kilometres travelled [28]. COPERT 5 version distinguishes between a broad variety of vehicles, considers urban, rural and motorways settings, and includes various factors related to “hot” emissions, “cold start” emissions, ambient temperature, fuel characteristics and non-exhaust emissions among others. The COPERT model was used, for instance, by Alam et al. [31] to recalculate the historical CO_2 emissions in Ireland for 1990–2013 taking into account the age of the vehicle fleet and the type of vehicle.

The emissions in the BAU scenario, and scenarios 1–4 (except for EVs) were calculated using COPERT based on the data presented in the previous section. Information on emission factors for the different drivetrains (ICEV, HEV, PHEV), fuels (petrol, diesel) and technology (Euro standards) that were used are consistent with COPERT specifications and can be found in the official guidebook in section 3.4 Tier 3 method [29]. Regarding PHEVs, which operate in either charge-depleting or charge-sustaining modes, the emission factors were adjusted using utility factors of 0.5/0.5/0.2 for urban/rural/highway road conditions provided in COPERT as default [32]. This means that the PHEV taxis run on fuel half of the time in urban and rural settings, and a fifth while driving on highways. For charge-sustaining mode, petrol PHEVs' emission factors equal those of petrol HEVs and diesel PHEVs' those of diesel ICEVs according to specifications in COPERT. Running on battery, PHEVs are assumed to produce no emissions. The analysis of the EVs emissions is different in comparison to other vehicles. There are no exhaust emissions produced by these vehicles and therefore the analysis cannot be completed using COPERT. To fully assess the emissions, the EVs contained in the fleet should be included in post COPERT analysis. The method of calculating the CO_2 emissions for the EVs is based on a CO_2 emission factor for electricity generation and the make and model of the EV. The emission factor for electricity was 295.8 g CO_2/kWh in 2020 [33]. This factor is used in conjunction with each EV's vehicle specifications to calculate the emissions produced to power the vehicle. The annual kilometres driven is divided by the range to calculate the number of charges that are required. The CO_2 emissions calculated for the current EVs in the fleet (456 vehicles) are presented in Table A-6 and are equal to 999.2 tonnes of CO_2 in total.

2.3. Scenarios

The scenarios were developed to investigate the phasing out of ICEVs and associated emissions. The intention set out by the government is that every vehicle in Ireland will be electric by 2030, but this cannot happen instantaneously. The five scenarios are designed considering a different pace of EV uptake (Table 1).

2.4. Cost-benefit analysis

To quantify the costs for the exchequer and environmental benefits associated with each scenario change, the CBA analysis that considers capital costs and emission costs is completed.

Capital costs refer to the incentives offered by the government for taxi drivers switching from ICEVs to EVs and include a grant for installing a home charging point (€600), grant for the purchase of a new EV (€10,000 plus €2500 to convert to wheelchair accessible vehicle), and scrappage scheme for replacing older vehicles with EVs (€20,000 or €25,000 if wheelchair accessible) [34]. The grant for the home charger is applied to all vehicles. The grant for scrapping old vehicles is assumed to be for vehicles older than 10 years. For this reason, this grant is applied to all ICEVs lower than a Euro 5. It is also assumed that any vehicle falling into the category of the large-SUV-executive or light commercial vehicle will require wheelchair accessibility.

The Common Appraisal Framework [22] is used to apply a monetary value to each of the emissions produced in each scenario. The price per tonne of CO_2 changes annually and stands at €46 in 2022. Monetary values for the non-greenhouse gases are €5688 for NO_x and €1398 for VOCs.

2.5. Multi-criteria analysis

The MCA approach is used to compare each scenario based on specified criteria on a point scaling system. Each criterion is broken down into sub-criteria (Table 2). The MCA is used to assess the impact of implementing each scenario and the results can be used to design future transport policies. Typically it is used for projects that will cost between €5 million and €20 million [22].

Table 1
Scenarios of phasing out internal combustion engine vehicles in the Dublin's FREE NOW taxi fleet.

Scenario	Description
Business as usual (BAU)	The current composition of the fleet (see Table A-5).
S-1 Removal of all ICEVs lower than Euro 5	In S-1 scenario any ICEV that falls under this category is divided between the Euro 5 and Euro 6 vehicle types. The HEVs and EVs remain the same as in the BAU scenario (see Table B-1).
S-2 Removal of all ICEVs lower than Euro 6	All Euro 5 ICEVs are removed from the fleet and replaced with Euro 6 vehicles (see Table B-2).
S-3 Complete removal of all ICEVs	All ICEVs are removed and replaced with a combination of the different types of HEVs. Petrol ICEVs are upgraded to petrol HEVs of Euro 4, 5 or 6 standard, and diesel ICEVs to petrol PHEVs of Euro 6. COPERT does not provide an option for a light commercial vehicle in the hybrid category. For this reason, the Large-SUV-Executive option is selected for these vehicles (see Table B-3).
S-4 Removal of all non-PHEVs	The petrol HEVs are removed and replaced with PHEVs Euro standard 6. The older PHEV vehicles are also removed and only the Euro 6 remains (see Table B-4).
S-5 Full electrification of the fleet	The entire fleet represented in the BAU scenario is converted to EVs. The original composition of each make and model in the current stock configuration is used to calculate a percentage for the projected fleet (see Table B-5).

Table 2
Assessment criteria for the multi-criteria analysis.

Criteria	Sub-criteria	Description
Economy	Capital Costs	Accumulative costs of grants
Safety	Vulnerable road users	Pedestrians
		Cyclists
Environment	Air quality	Reduction in emissions
	Noise and vibration	Reduction in noise and vibration
	Lifetime assessment	Reduction in emissions over the life span
Accessibility	Vulnerable groups	Increase in wheelchair access
Vehicle owner	Personal costs	Purchase price
		Price of fuel or energy
		Maintenance
Infrastructure	Requirements	Access to charging stations

In the MCA analysis, the costs related to the economy are valued using the capital costs that the government is providing in the form of grants as previously specified (Section 2.4).

The safety analysis refers to cyclists and pedestrians. The positive or negative impact on these road users relates to the level of pollutants that they are subjected to on the roads from the taxi fleet.

The environmental assessment for the air quality is completed using the monetary values placed on the emissions described in Section 2.4. The noise and vibration are determined by the noise produced by a dominant vehicle type in each scenario in reference to the literature. The final aspect of the environmental assessment is the life-cycle assessment (LCA) of each vehicle fuel type. To quantify each scenario in relation to their LCs we use the analysis presented in Shafique et al. [35] and Tagliaferri et al. [36] which indicate that EVs have the lowest environmental impact, diesel PHEVs are the second best, followed by petrol PHEVs. The worst powertrain types are the HEVs and ICEVs.

The accessibility will be assessed in terms of the availability of wheelchair-accessible vehicles. In the case of the EV, the wheelchair access reduces the range of the vehicle as additional power is needed for increased weight. To mitigate this impact, more expensive vehicles with a larger battery capacity are required.

The impact of each scenario on the owner of the vehicle is also included in the MCA. Personal costs refer to the costs that will be placed on the driver of the taxi when changing to an EV. The grants offered by the government will not be enough to encourage the change to EVs if the personal costs are too high and the charging infrastructure is not available. In many cases, the purchase price for the EV, even including the grant, is quite high. The purchase price of each EV is the price of a brand new 2022 vehicle and all pricing includes the government grant of €5000 for private vehicle owners (Table B-6). The cost of fuel or energy and the maintenance of the vehicles are also assessed. The warranties provided by the EV manufacturers are considered (Table B-7).

Each criterion is assessed using a point scale system from 1 to 6 as

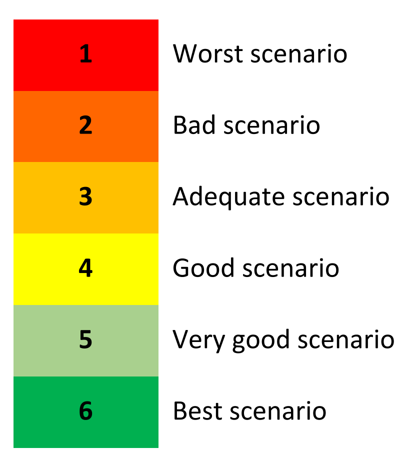

Fig. 1. Point scaling system.

there are five scenarios and the BAU. The scale system is presented in Fig. 1.

3. Results and discussion

3.1. Scenario analysis

The main focus of this study is to examine the emissions produced by the taxi fleet in Dublin and implement changes in the fleet to reduce and, eventually, completely remove the tailpipe emissions. The emissions from the BAU and each scenario for all vehicles except EVs were calculated in COPERT (Table C-1, C-2, C-3, C-4). As the process for calculating the emissions for the EVs was not completed in COPERT, for the BAU and scenarios 1 to 4, the total tonnage calculated will be added to the total emissions produced in COPERT for each scenario (Table C-5). The emissions from scenario 5 were entirely calculated using the EV emissions estimation method described in Section 2.2.

The comparison of resultant emissions against the base case is shown in Table 3, including also a percentage difference to BAU for each scenario 1 to 5.

In S-1, the ICEVs below Euro 5 are removed from the fleet and replaced with Euro 5 and Euro 6 vehicles. This is most likely to be a real-life scenario as scrapping an old vehicle is more likely than a new one. Compared to the BAU case there are small reductions in each of the emissions. The CO_2 emissions have only decreased by 58.75 tonnes. As with the BAU, the highest producer of NO_x is the diesel vehicle. Conversely to the BAU, the highest producer of CO_2 is the diesel medium-sized Euro 5 vehicle, followed closely by the diesel Euro 5 light commercial vehicle. These vehicle types comprise the largest proportion of the fleet. The lowest producers of CO_2 are the petrol PHEVs with the caveat that the CO_2 emissions from producing electricity when the vehicles run on the electric battery were not taken into account. This means that in reality, these emissions would be higher than estimated. Nonetheless, the petrol PHEVs produce zero VOCs and these are also the better-performing vehicles in relation to NO_x.

Following on from S-1, in S-2 all Euro 5 ICEVs are replaced with Euro 6 ICEVs. The hybrid vehicles remain the same. This scenario shows large reductions in NO_x. The change in CO_2 emissions is still relatively low at 24.81 tonnes. In this scenario, the highest contributors to CO_2 emissions are the medium Euro 6 diesel vehicles which produce 30,179 tonnes of CO_2, followed closely by the diesel Euro 6 light commercial vehicles. Removal of these vehicles would have a large impact on the overall resultant CO_2 emissions. Throughout the analysis of S-1 and S-2, the vehicles that produce the lowest emissions remain to be the hybrid vehicles, but in particular, the PHEVs. Worth mentioning again that these vehicles were assumed to not produce CO_2 when running in charge-depleting mode.

In S-3, all ICEVs have been removed and replaced with a fleet that consists of a combination of different hybrid vehicles. The removal of all ICEVs results in a higher reduction in CO_2 emissions compared to the BAU than each of the previous scenarios combined. This shows the importance of the removal of all ICEVs from the current taxi fleet. The vehicles producing the highest CO_2 emissions in this scenario are the petrol hybrid vehicles, in particular, the Euro 4 vehicles. The petrol HEVs are also the highest producers of VOCs. The large diesel PHEV is the highest producer of NO_x. As shown, there is an increase in this scenario in VOCs in comparison to the BAU.

S-4 involves the removal of hybrids below Euro 6 to be offset to all PHEVs. As known from the results of each previous scenario, the emissions are considerably lower for PHEVs. In the original fleet, there were only 20 diesel PHEVs, while in this scenario they account for 27% of the total fleet. The remainder consists of petrol PHEVs at 69% and EVs at 4.5%. This scenario produces the highest reductions in emissions for each species, but the overall reduction in CO_2 emissions is comparable to S-3 and thus not sufficient to favour this scenario over S-3.

The final scenario using COPERT (S-4) has shown that even with a complete upgrade of the fleet to PHEVs the reduction in emissions is not substantial enough. The removal of all ICEVs was not enough. Full electrification needs to be completed to fully analyse the impact. The overall reductions in percentages from the BAU are relatively low when considering the changes that need to occur to fulfil the target of zero emissions by 2030. The scenarios containing the ICEVs, as shown, had very little change even when restrictions were made on the Euro standard. Even in scenario 4 with all PHEVs, the CO_2 emissions were only reduced by 29%.

S-5 is the complete replacement of all vehicles in the fleet by EVs. The emission reductions from S-5 are the most substantial of all the scenarios.

3.2. Emissions analysis results

This section consists of an analysis of the emissions produced by each scenario: CO_2, NO_x, and VOCs.

Each scenario produces less CO_2 than the BAU, but in the case of S-1 and S-2, with different combinations of ICEVs, the reduction was negligible (Fig. 2). The largest change was caused by the overhaul of the fleet to completely electric. The on-road CO_2 emissions produced by the EVs would be zero and therefore the analysis took into consideration the electricity used by the vehicle. Even considering this aspect of the EV, the emissions produced were significantly lower than that of any of the other vehicle types. This change in vehicle engine type produced a reduction from the BAU of 77%. This is a significant decrease, but it is not completely carbon neutral. The promotion of the EV as a zero-emission vehicle is untrue when the source of the electricity is considered. However, there is potential for further emission reduction considering the future increase in the share of renewables in electricity production.

VOCs are a contributing source of ground-level ozone due to reactions with NO_x [37]. The non-methane VOCs have the potential to cause severe and irreversible damage to people's health as these contaminants are extremely toxic [38]. The emissions produced from an exhaust of a vehicle are considered to be a major source of VOCs [39]. There was a small decrease in these pollutants in S-1 and S-2 at approximately 10%. In S-3 all ICEVs were removed and replaced with petrol HEVs, which caused an increase in VOCs. Older HEVs were used in this scenario which produced higher emissions. The emissions produced by the PHEVs were relatively low for S-4.

NO_x is a contaminant released from the exhaust of an ICE [40]. Older vehicles are particularly at fault for the release of this emission, as clearly shown in Fig. 2 for S-1. A small change in scenario 2 with the removal of the older ICEVs lower than a Euro 5 reduced this emission significantly with an 85% reduction from the BAU. The introduction of EVs in S-5 entirely removed these emissions produced by the exhaust. The Irish government introduced a tax on NO_x emissions which began at the start of 2020 that does not apply to EVs but does include HEVs and PHEVs [41]. This is in an effort to reduce the vehicles on the road that

Table 3
Resultant emissions in tonnes from each scenario.

Emission	BAU	S-1	Diff.	S-2	Diff.	S-3	Diff.	S-4	Diff	S-5	Diff.
CO_2	86,196.37	86,137.62	−0%	86,171.56	−0%	62,045.64	−28%	60,970.27	−29%	19,554.06	−77%
NO_x	191.98	184.04	−4%	29.16	−85%	13.89	−93%	10.30	−95%	0.00	−100%
VOCs	15.05	13.86	−8%	13.85	−8%	16.73	+11%	5.27	−65%	0.00	−100%

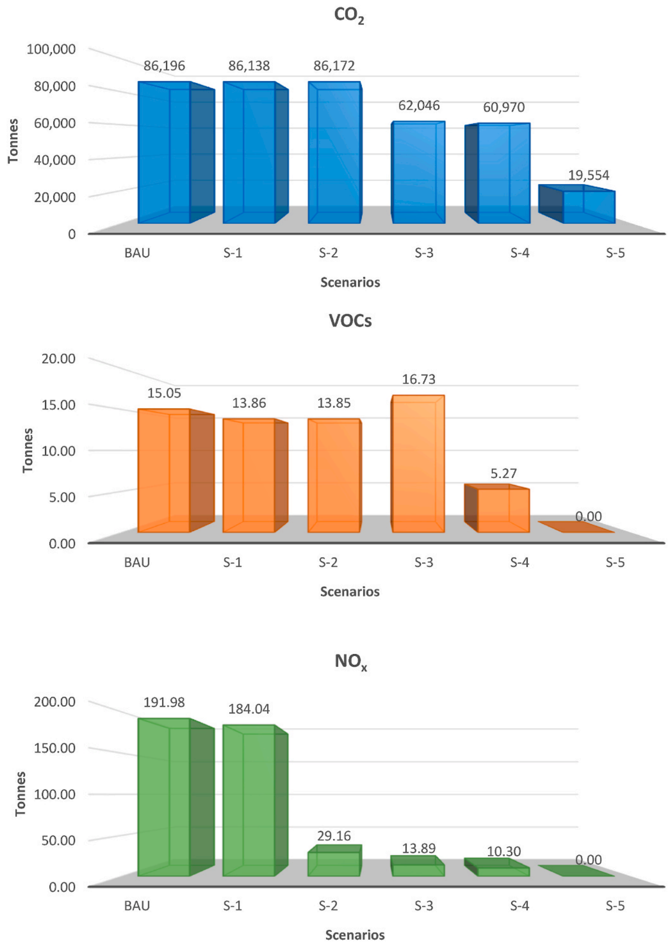

Fig. 2. CO_2, VOCs, and NO_x emissions produced from each scenario.

produce high levels of NO_x. Diesel vehicles are more impacted by this tax as they produce higher levels of this pollutant.

3.3. Cost-benefit analysis results

The CBA conducted in this study compares the capital costs for the exchequer with environmental benefits drawn from emission reduction expressed in monetary values. The capital costs apply only to the S-5 scenario as grants are offered only for the purchase of EVs. We assume no cost to the exchequer in other scenarios.

The government incentives are applied to the current FREE NOW taxi fleet and the capital costs are produced for the complete change of the fleet to an electric fleet. The total capital expenditure of €123, 787, 827 includes €118, 031, 427 of the government's grants for the purchase of new EVs and €5,756,400 grants for installing home chargers (Table C-6).

Each emission is given a monetary value and each scenario is compared to the BAU. The total cost of emissions in the BAU scenario is €5,078,071. The cost breakdown for each pollutant in all scenarios can be found in Table C-7. The comparison is shown using the percentage difference to the BAU in Fig. 3.

As shown in Fig. 3, the cost of the emissions reduces from scenario to scenario with the highest benefits produced by S-5. S-5 consists of all EVs and presents the lowest cost at 18% of the BAU. S-1 and S-2 produce similar costs as the BAU, whereas S-3 and S-4 consisting of HEVs, are significantly lower at 58% and 57%. Both of these scenarios present similar results.

It should also be noted that in comparison to the reductions in emission costs, the capital costs produced by the full electrification of the fleet in a form of government grants are incomparable. The total

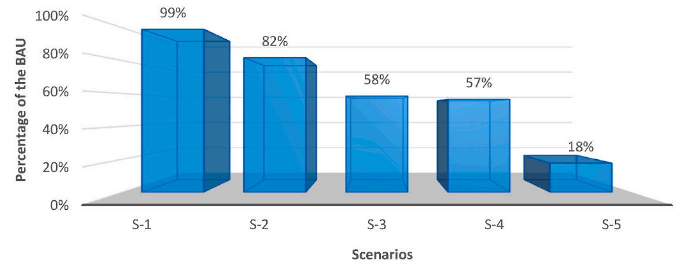

Fig. 3. Comparison of the cost of emissions for each scenario as a percentage of the business-as-usual.

reduction in emission costs from the BAU in scenario 5 is roughly €4 million, but the cost of providing grants to every taxi driver in the FREE NOW fleet is almost €124 million. It shows that the policy is not sustainable in long run and only a fraction of the taxi drivers in Ireland will benefit from these incentives.

3.4. Multi-criteria analysis results

The MCA was completed using a point scoring system from 1 to 6, for a chosen set of criteria. The scoring is applied to each scenario, with 1 being the least favourable scenario and 6 being the best. The totals were added together and an average is taken to assess the scenario representing the most favourable recommendation. The compilation of the MCA is shown in Table 4..

The criterium of capital costs is based on the costs that the state would have to pay out to the FREE NOW taxi owners to change to an EV. These costs make the switch to EVs the most expensive option for the exchequer. As there are no grants provided for buying a newer vehicle or the purchase of an HEV, the negative impact of the capital costs is only applied to the change to EVs.

For many of the criteria, the EV fleet in S-5 received higher scores than any of the other scenarios. For pedestrians and cyclists the reduction in exhaust emissions will provide cleaner air quality. For the environmental criteria, the cost of emissions was used to analyse the impact of emissions reduction in each scenario. As shown in Fig. 3, the cost gradually decreases with each scenario from S-1 to S-5 and this was reflected in the scores. S-5 also scored highly for noise and vibration. S-1 and S-2 consist of a majority of ICEVs which are louder than HEVs and EVs. S-3 and S-4 are given the same score. The noise and vibration produced by the HEVs as the additional parts are required cause increased vibration and louder noise compared to EVs [42]. In the case of life-cycle assessment, as classified in Section 2.5, the points are distributed according to findings in Shafique et al. [35] and Tagliaferri et al. [36].

The assessment of the vulnerable groups and accessibility is based on the number of wheelchair-accessible vehicles in the fleet which is highest for S-5. The scenarios that scored the lowest for accessibility were S-3 and S-4 as there were no multi-purpose vehicles in these fleets. In S-5 there was a large number of multi-purpose vehicles, but the extra weight requirements will impact the range. For this reason, there are higher purchase costs involved in buying an EV with a higher battery capacity.

In relation to the purchase price, the cost of a new EV is higher than the cost of an ICEV, however similar to ICEV with a grant applied. For this reason, BAU and S-5 were identified as the best scenarios. HEVs cost more than ICEVs, for instance, an HEV Toyota Yaris and an ICEV Toyota Yaris can be purchased at €24,470 and €21,250, respectively [43]. The difference between the purchase price of a PHEV and an HEV is that the PHEV is estimated as costing 10% more than the HEV [44]. The EV fleet advantage depends on government grants which can change at any time. It is not sustainable to continue subsidies, past a certain point.

The fuel costs are similar for BAU, S-1 and S-2 as they all have the

Table 4
Multi-criteria analysis results for business-as-usual and five scenarios of phasing out internal combustion engine vehicles.

Criterium	BAU	S-1	S-2	S-3	S-4	S-5
Accumulative costs of grants	6	6	6	6	6	1
Pedestrians	1	2	3	4	5	6
Cyclists	1	2	3	4	5	6
Reduction in emissions	1	2	3	4	5	6
Reduction in noise and vibration	1	1	1	3	3	6
Reduction in emissions over the life span	1	1	2	3	5	6
Increase in wheelchair access	5	5	5	1	1	6
Purchase price	6	5	3	2	1	6
Fuel costs	1	1	1	4	5	6
Maintenance	1	2	3	4	5	6
Access to a power source	6	6	6	6	6	1
Total	30	33	36	41	47	56
Average	2.73	3.00	3.27	3.73	4.27	5.09

same number of ICEVs. Currently, the price of petrol and diesel is at the highest. For this reason, the scores given to the BAU, S-1 and S-2 are the lowest. HEVs use less petrol than an ICEV, and PHEVs use less petrol and diesel than HEVs according to utility factors that were assumed. The power required to run an EV does not cost as much as petrol and diesel [45] and for this reason, S-5 was flagged as the best scenario. The maintenance costs were high for ICEV, in particular the older vehicles. These costs gradually decrease from S-1 to S-4 scenarios as the older vehicles were replaced with newer ones. In addition, PHEVs that were introduced to the fleet in S-4 need less maintenance than ICEVs and HEVs as less frequent oil and filter replacements are required [46]. The EVs are the best scenario due to the longevity of the warranties provided by most manufacturers. In many cases this warranty is given in years or before a certain mileage is reached. In the case of the taxi owner, this mileage may be reached before the given timeframe.

The final criterion is access to a power source. Petrol and diesel are readily available all over the country, while the charging facilities for EVs are not always nearby and planning a journey does require investigation into the charging available. For this reason, the EV is the worst scenario. Currently, taxi drivers of EVs are charging their vehicles at home overnight. The implication of more than one EV at a dwelling could compromise this routine. Moreover, the available number of 38 charging locations in the city centre [47] would not accommodate the 456 EVs in the current FREE NOW fleet and huge developments are required in the charging infrastructure to accommodate the planned 1 million EVs [48].

Overall, S-5 received the highest score with an average of 5.09, followed by S-4 with 4.27. S-4 consisted of all PHEVs and is the more environmentally friendly option when an EV is too expensive or access to suitable charging infrastructure is not provided.

4. Conclusions

The emissions produced by the transportation sector are a major contributing factor to global warming. The FREE NOW taxi fleet has pledged to be completely carbon neutral by 2030. The focus of this research was to analyse the reduction in GHG and non-GHG emissions from changing the composition of the taxi fleet and using different fuel types. Dublin's FREE NOW fleet was used as a case study to show the feasibility of the company's target and, more broadly, the viability of electric transition for taxis, its benefits and barriers to the implementation of this strategy. The analysis revealed what configuration of vehicle technologies would present the highest emission abatement in terms of pollutants emitted and their monetary value. This is useful insight for policymakers at the municipal and national levels and also for businesses to inform their decision regarding support for electric technology for taxi vehicles and the optimal ICE phasing-out strategy. The findings from this study seem especially important when considering global commitments to EV technology as a critical element of transport sustainability and the role that the taxi industry plays in accelerating EV uptake. The evidence presented in this research and summarized below strengthens the argument for increasing the pace of adopting EV technology in taxi fleets and advancing public charging infrastructure provision.

The FREE NOW fleet in 2021 is used as the BAU case, to which five scenarios are compared. Each scenario represents a different combination of engine types. The emissions produced from the BAU and S-1 to S-4 were calculated using COPERT, and the emissions produced by the electricity used to power the EVs in S-5 were calculated using a CO_2 emission factor. The results of the analysis showed that the change to a fully electric fleet reduced the total CO_2 emissions produced by 77% in comparison to the BAU. The second more favourable option was S-4, which consisted of all PHEVs.

Changing every taxi vehicle to an EV, even when the electricity used to power the EV was taken into consideration, significantly reduces CO_2 emissions. However, even though emissions from the exhaust of an ICEV are eliminated, non-exhaust emissions are also produced in the form of PM. PM comes from tyre wear, brake wear, road wear, and resuspension of vehicles. EVs produce a higher level of PM due to the greater weight of the vehicle but on the other hand, regenerative braking reduces brake wear emissions. This results in negligibly fewer non-exhaust PM emissions produced by EVs compared to ICEVs [27]. The EVs might be lighter in the future because of battery improvements and materials used [49], however, it is uncertain considering a steady trend to increase vehicle size and demand for longer EV range that requires heavier structure [27]. Furthermore, non-exhaust PM is still not regulated and validation of emission factors is needed [50]. Progress in this matter is expected to be made with the introduction of Euro 7.

The current FREE NOW taxi fleet consists of 0.7% PHEVs and 4.5% EVs. This is extremely low for the target of all EVs to be accomplished by 2030. The growth rate would need to improve significantly. The research has shown that government grants provided will increase the growth rate, but the charging infrastructure must improve for this to happen. The Irish government is developing strategic plans to tackle this issue, but the timeframe is unknown as of yet. The government is proposing a €100 million investment for charging infrastructure. A greater focus on electrifying the city's bus fleet may also provide some synergies and accelerate the delivery of charging stations that simultaneously would support electric taxis. Relying only on home charging is a problematic issue for taxi owners in Dublin and other large cities where the majority of people live in apartments and flats. In Ireland, the government provided plans in the draft for charging in apartments and residential communal charging. In Dublin, where not all houses have driveways and on-street parking is the main means of parking in the city, residential charging may be a solution to this.

The capital costs accrued by the state for the continued grants provided have a short shelf life. This grant will not be available to all taxi owners that wish to change to an EV in the next few years. This grant is also only accessible to those who can afford to buy an EV, as the purchase price of an EV is significantly higher than that of its alternative ICEV. Those on lower incomes cannot avail of the grant as even with the grant they have a financial barrier to adopting EVs [[51]]. It has been concluded that the purchase price has a huge impact on the sales of EVs.

The scenarios were assessed under a variety of criteria using MCA. The S-5 scenario assuming electrification of the whole taxi fleet scored the highest in most of the criteria, but the charging and continuation of the grants are an issue. The emissions calculated using COPERT and the emission factor used to quantify the emissions produced from the electricity used for powering the EV were all compared in the MCA. The EV contributes fewer emissions through charging and its lifetime than the other vehicle fuel types. It is a solution to the current air pollution issues, but it is not the only solution and more emphasis should be placed on pedestrian and cycling infrastructure and public transport. In the case of the electrification of the taxi fleet, it is a viable, sustainable option that should be implemented, with extended government grants and investment in adequate charging infrastructure.

This research is limited in some aspects and based on certain assumptions. First, the emissions produced by the EV fleet were calculated using an emission factor from 2020 for electricity. These factors change yearly, which means the actual value of the CO_2 emissions produced, could be lower depending on the source of the electricity. Second, PHEVs were assumed to produce no CO_2 emissions when running on battery, hence the real emissions would be higher than estimated for these vehicles. Third, the data provided by FREE NOW was limited. This problem was resolved by developing assumptions to classify the vehicles in the data. Errors may have occurred during this process, but the assumptions were based on known statistics and were developed to be as precise as possible. Fourth, the data on average speed per trip was not available, thus the speed limits were used in the model instead. This is also because there was no basis for having lower values than speed limits. Fifth, the LCA was not performed in this study as being beyond the scope. In the absence of LCA provided for Irish conditions, the major findings from European and international studies were considered in determining the ranking of the environmental impact of vehicle types.

The EV analysis was completed using specifications provided by the car manufacturers and was based on brand-new vehicles. Future research could consider older EVs, and in particular the second-hand sale of these vehicles. To extend the analysis completed in this study on the reduction of the emissions produced by the FREE NOW taxi fleet by changing the fleet to fully electric, more research into the re-sale of the EVs and the end-of-life disposal would be beneficial. Potential research direction could also consider the emission reduction from electrifying the mobility-as-a-service (MaaS) fleet as a whole on a selected case study or estimate emission savings from an electrified fleet of connected and autonomous vehicles (CAV).

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors, but the authors acknowledge Trinity College Dublin, the University of Dublin, Dublin, Ireland for supporting the open access publication of this article.

Credit author statement

Laoise Kinsella: Conceptualization, Methodology,Software, Validation, Formal analysis, Investigation, Brian Caulfield: Conceptualization, Methodology,Software, Validation, Formal analysis, Investigation,Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization,Supervision, Project administration, Project administration, Funding acquisition; Agnieszka Stefaniec: Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization: Aoife Foley; Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113160.

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