MICRO-ANALYSIS OF THE FUELLING COSTS OF ELECTRIC VEHICLES IN CONSIDERATION OF THE RANGE OF OPTIONS AVAILABLE TO ELECTRIC VEHICLE USERS

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ABSTRACT
It is common knowledge that the costs of powering electric vehicles (EV) are less than the fuelling costs of internal combustion engine vehicles (ICEV) due to the relative per-unit prices of electricity and gasoline, respectively, which enhances the consumer acceptance of electromobility as a viable alternative to ICEV usage. However, whilst ICEV users do not have a choice regarding how to fuel their vehicles since they must make use of fuelling stations, EV users have a number of options with respect to where, when, and how to recharge their vehicle batteries. This paper presents a micro-analysis of the costs associated with the various choices available to EV users and the effects of these differing methods on the overall costs of running EVs. Comparisons are made to fuelling costs of ICEVs, wherein the potential effects of rising gasoline prices are estimated. Whilst the cost analysis is primarily conducted within an Irish context, fuelling costs in additional countries are also considered. The results show that the choices EV users make with respect to how to charge their vehicles have a large impact on the fuelling costs of EVs. Substantial savings can be accrued by EV users through their selection of charging method. It is recommended that the fuelling costs of EVs and comparisons to ICEV costs should be publicised to expand consumer awareness.

Keywords: Electric vehicles, fuelling costs.

INTRODUCTION AND BACKGROUND

In a review of the barriers to EV deployment, the National Research Council *(1)* highlighted the cost of EVs as a particularly prominent barrier inhibiting EV adoption; however, it is frequently the case that possible EV consumers do not consider the contrasting costs of running EVs and ICEVs within their vehicle-purchasing decisions *(2).* Many studies have found that EVs become cost-competitive with ICEVs when factoring in the total cost of ownership (TCO) of the vehicles *(3,4)*; paramount to the lower costs of running an EV when compared with an ICEV is the cost of fuelling the vehicles due to the respective costs of electricity and gasoline. Vehicle consumers may not fully appreciate the extent to which the fuelling costs of EVs and ICEVs differ as suggested by a stated preference survey that found information on fuel cost savings did not influence consumers to choose an EV *(5).*

Previous studies have estimated the potential fuel cost savings associated with EV usage compared with ICEVs in a variety of contexts, primarily focusing on the United States. Wishart *(6)* examined fuel and ownership cost reductions using average gasoline and electricity prices and the average annual mileage travelled in the US. Average annual fuel cost savings of 75% were estimated, and in conjunction with federal tax credits a reduction in the five-year cost of ownership of an EV of 11% was estimated when compared with a mid-sized ICEV.

Anair and Mahmassani *(7)* investigated the possible fuel cost savings resulting from driving an EV rather than an ICEV in each of the fifty biggest cities in the United States. It found that EV owners would save money in each city when compared to the average compact gasoline vehicle, regardless of the electricity pricing plan used by an individual – annual savings ranged from $50 to $1,220, dependent on the city. Both the Wishart *(6)* and Anair and Mahmassani *(7)* studies were based on a macro-analysis.

It is widely reported that the actual real-life fuel consumption rate of an EV greatly differs from the manufacturer-stated fuel consumption rate due to driving style, temperature, and the types of roads on which the vehicle is travelling *(8).* The costs of electricity and gasoline differ between countries and as such this subsequently has an impact on the fuelling costs of EVs and associated comparisons to ICEVs *(9, 10).* Many governments and charge point manufacturers have introduced membership schemes for EV users, primarily based on a monthly or annual membership fee, which have been received with a sometimes-negative response from consumers *(11, 12).* Fiscal incentives have also been examined in the context of promoting electric vehicles *(13).* These aspects can add to the confusion regarding the fuelling costs of EVs.

An investigation into consumer behavioural adaption in EV fast charging through pricing found that a flat-rate fee has a negative effect on the usage efficiency of fast chargers *(14)*. Other researchers found conflict between PHEV drivers and the government objectives; cost-effective charging should take place in the morning while eco-friendly charging should take place late afternoon *(15)*. A very large penetration of PHEVs would place increased pressure on peak unit consumption if charging is completely uncontrolled *(16)*.

Few previous studies have focused on the myriad of fuelling options that are available to EV users. This can result in the fuelling costs of EVs being under- or over-estimated, and the comparisons to the fuelling costs of ICEVs may be misrepresented. The primary objective of this study is to conduct an in-depth micro-analysis of the fuelling costs of EVs paying particular attention to the range of fuelling options available to EV users. Aspects covered include electricity pricing, public charging costs, free electricity for charging, electricity pricing plans such as time of use (TOU) rates, differing vehicle usage levels and varying future electricity pricing forecasts. Comparisons are made to the fuelling costs of ICEVs and differing future gasoline price forecasts are incorporated. Whilst the analysis is based in an Irish context, analyses are additionally conducted for other countries. The effects of driving style on the fuelling costs are determined using data emerging from vehicles in an EV trial. Other elements within the analysis include the impact of membership schemes on the costs of EVs and the potential increases in annual electricity bills.

MATERIALS AND METHODS

The fuelling cost calculations within this study are focused on the Nissan Leaf EV *(17)*, currently the world's all-time highest-selling EV with over 200,000 vehicles sold *(18)* and since it is a mid-sized passenger vehicle. The Nissan Leaf has a 24 kWh battery and an associated maximum driving range of approximately 199 km. The fuel costs are primarily based on the manufacturer-stated fuel consumption rate, which is recorded as 150 Wh/km based on the New European Driving Cycle phase 1 (NEDC(1)) *(19)*. A supplementary analysis will compare the manufacturer-stated fuel consumption rate of an EV with the actual fuel consumption rate of an EV utilising real data emerging from EVs deployed during an extensive EV trial *(20)*. Comparisons of the fuelling costs between EVs and ICEVs are conducted with respect to the Nissan Leaf EV and the Nissan Note ICEV *(21)* – this is due to the similarities in vehicle manufacturer, usages, and weights between the EV and ICEV. The Nissan Note has a manufacturer-stated combined fuel consumption of 4.7 L/100 km, and an emission rate of 109 gCO_2/km. It can be noted that whilst the primary focus will be on the Nissan Leaf and Nissan Note, inferences are additionally made on other vehicle makes and models.

The fuel cost calculations encompass a five-year analysis period, similar to the methodologies incorporated by Dumortier et al. *(5)* and Kelley Blue Book *(22)*. The five-year analysis period is used in order to account for possible increases and decreases in the prices of electricity and gasoline *(9)*. The base year for the analysis is 2016, allowing the study to cover the period from 2016 until 2020. The fuelling costs are calculated by multiplying the manufacturer-stated fuel consumption rate by the fuel prices for each year and the distance travelled in the vehicles. Three usage levels are used in the analysis: Low-Usage, where it is assumed a vehicle travels 6,000 km annually; Mid-Usage, which accounts for an annual distance of 12,000 km; and High-Usage, representing an 18,000 km annual distance. The chosen distances are based on the typical average distances driven by varying categories of EV users *(20)*.

In order to account for the myriad of charging options facing EV users and the effects of these options on the fuel costs of EVs, a hierarchical structure is devised in order to effectively present the fuel cost results which takes into account differing electricity pricing plans and usage statistics. Information sourced from Bonkers, an internet company accredited by the Commission for Energy Regulation (CER) of Ireland as being an impartial, accurate, and independent supplier of energy prices, is used in a determination of the possible increases in a household's electricity bill with the inclusion of an EV *(23)*. The potential effects of public charge point membership schemes on the overall fuelling costs of EVs will be investigated, specifically in relation to a scheme proposed by the Irish government *(12)*. With respect to the comparisons between EV and ICEV fuelling costs, differences between the prices of gasoline and diesel will be discussed, and differing gasoline price forecasts for each fuel type will also be explored.

Costs of Fuel

Fuel Cost Forecasts

The average Irish price of €1.37/L ($1.6/L) for gasoline in 2015 was used along with an average price of diesel of €1.26/L ($1.48/L). For the base electricity price, 26 individual domestic electricity pricing plans were used in order to obtain an average base price for 2016 using data sourced from Bonkers – the base price of electricity for 2016 was €0.1663/kWh ($0.19/kWh) *(24).* The price of electricity in Ireland varies depending on the pricing plan chosen by an individual, whether a smart meter is used offering cheaper night-time tariffs, and whether domestic or industrial electricity pricing is considered, with industrial pricing accounting for a situation wherein a business incorporates EVs into its fleet of vehicles – each of these aspects will be discussed further in the following section.

Prices of gasoline and diesel have fluctuated greatly in recent years from €0.79/L ($0.93/L) for gasoline and €0.73/L ($0.85/L) for diesel in November 2001 to a high of €1.70/L ($1.99/L) for gasoline and €1.60/L ($1.87/L) for diesel in September 2012 *(25).* Similarly, electricity prices have significantly changed from an average domestic low of €0.095/kWh ($0.11/kWh) in 2000 to an average domestic high of €0.182/kWh ($0.21/kWh) in 2014 *(26,27,24).* To reflect such changes, three different fuel cost forecast scenarios are included within the study using a basic scenario analysis. Scenario 1 assumes that the prices of fuel remain constant throughout the five-year analysis period; Scenario 2 applies to a price increase of 5% per annum; and Scenario 3 represents a 10% increase per annum. It can be noted that these scenarios are applied to the fuelling costs of both EVs and ICEVs; additionally, a supplementary analysis considers a situation where the price of fuel declines from current levels.

Electric Vehicle Charging Costs

Due to the cost of installing, maintaining, and administering public charging infrastructure along with higher daytime prices of energy, the cost of public charging exceeds the cost of domestic charging *(28).* Whilst public charging infrastructure in Ireland is currently free-to-use both as an incentive and due to the payment mechanism not yet being operational, the Electricity Supply Board (ESB), estimates that public charging will cost an EV user twice as much as the cost of charging in a household, and as such this definition is used within the current study *(29).* The prices of domestic and industrial electricity differ due to the EU Gas and Electricity Price Transparency Directive, which offers reduced taxes to industrial end-users *(30);* as such, commercial business could take advantage of the cheaper electricity costs in 2016 of €0.1135/kWh ($0.13/kWh).

As mentioned earlier, public charge points are currently free-to-use in Ireland and many companies offer free workplace charging to EV owning employees *(31).* Many countries including Ireland additionally incorporate TOU pricing which supplies cheaper electricity to consumers during night-time hours. Ireland's Commission for Energy Regulation (CER) is introducing a widespread smart metering programme which will enable EV users to benefit from cheaper night-time charging by programming their smart meter to begin the charging process during night-time hours *(32).*

Electricity price plans are offered either on a constant 24 hour basis or on a time-of-use basis, and the TOU plan is referred to as the NightSaver plan in Ireland, with the cheaper electricity rates beginning at midnight. The average cost of electricity under the 24 hour plan is €0.1663/kWh ($0.19/kWh), but for the NightSaver plan the average day rate is €0.1784/kWh ($0.21/kWh) and the night rate is €0.0880/kWh ($0.1/kWh) for domestic pricing. For industrial pricing the average cost of electricity under the 24 hour plan is €0.1135/kWh ($0.13/kWh) whilst the average day rate for the NightSaver plan is €0.1218/kWh ($0.14/kWh) and the average night rate is €0.0601/kWh ($0.07/kWh).

Fuel Cost Scenarios

In consideration of the many aspects of the fuelling costs of EVs a hierarchical structure was devised as a means of analysing the fuelling costs of EVs and displaying the results efficiently. The hierarchy begins with a specific EV consumption rate, expressed in kWh/km, which determines the quantity of energy required by the EV per kilometre. Electricity pricing is then divided into both domestic electricity pricing and industrial electricity pricing because of the differences in the tax imposed on these pricing scenarios. For each of the electricity price forecast scenarios it is assumed that a specific portion of charging is spent at public charge points, with three scenarios analysed: 0% public charging; 10% public charging; and 20% public charging. These levels are selected as an indicative example.

For each public charging percentage scenario, the effects of free-to-use public charge points are analysed under three scenarios: N/A, which accounts for the 0% public charging scenario; Yes, meaning the free public charge point electricity incentive is in effect; and No, which means it costs the EV user to use public charge points. Subsequent to this, three different electricity price plans are analysed: 24 Hour, which is assigned to the situation where electricity prices are constant throughout the day; TOU-N, which assumes that an individual charges their vehicle solely during the night-time hours of the NightSaver electricity plan, with no charging occurring during the day; and TOU-50, assuming 50% of charge events occur during the night-time hours of the NightSaver plan. Following these price plans, three vehicle usage levels are analysed for every scenario outlined above, assuming a different annual distance is travelled, which are labelled: Low-Usage (6,000 km/annum) (3,728 miles/annum); Mid-Usage (12,000 km per/annum) (7,456 miles/per annum); and High-Usage (18,000 km per/annum) (11,185 miles/annum). Figure 1 summarises the hierarchical structure of the EV fuel cost analysis. The ICEV costs are also calculated using a five-year analysis period, and the calculations take into account the same three vehicle usage levels and the three gasoline price forecasts.

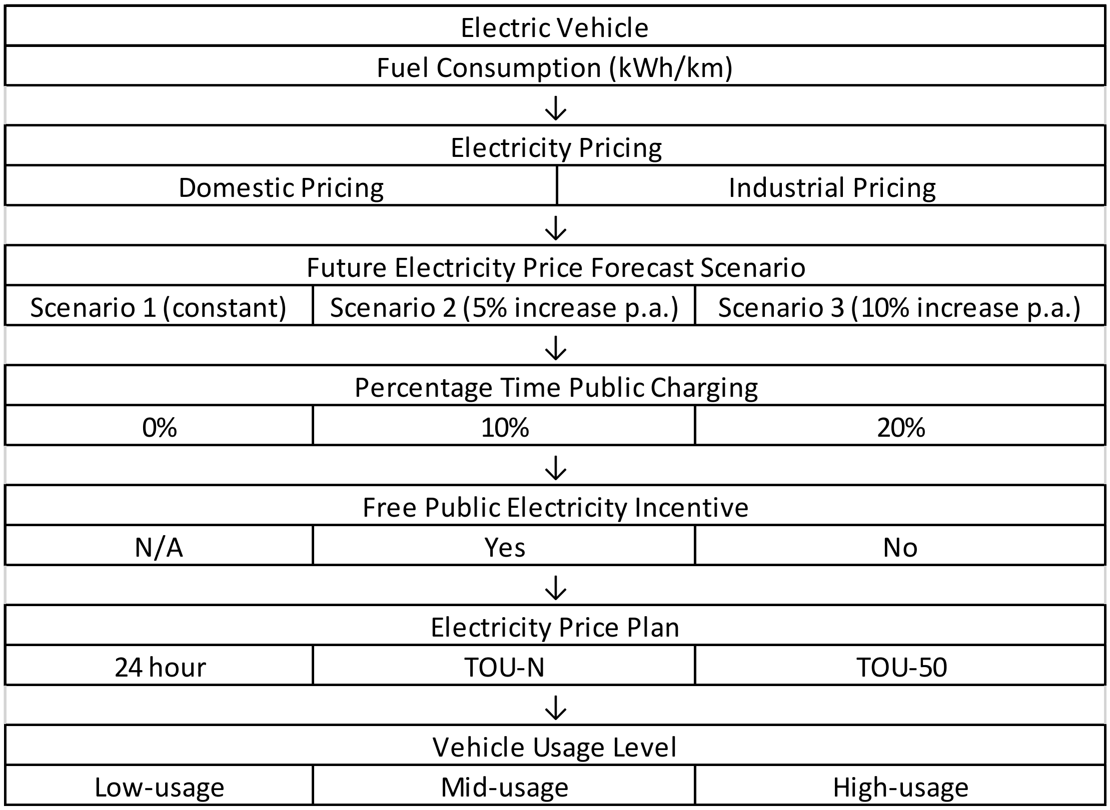
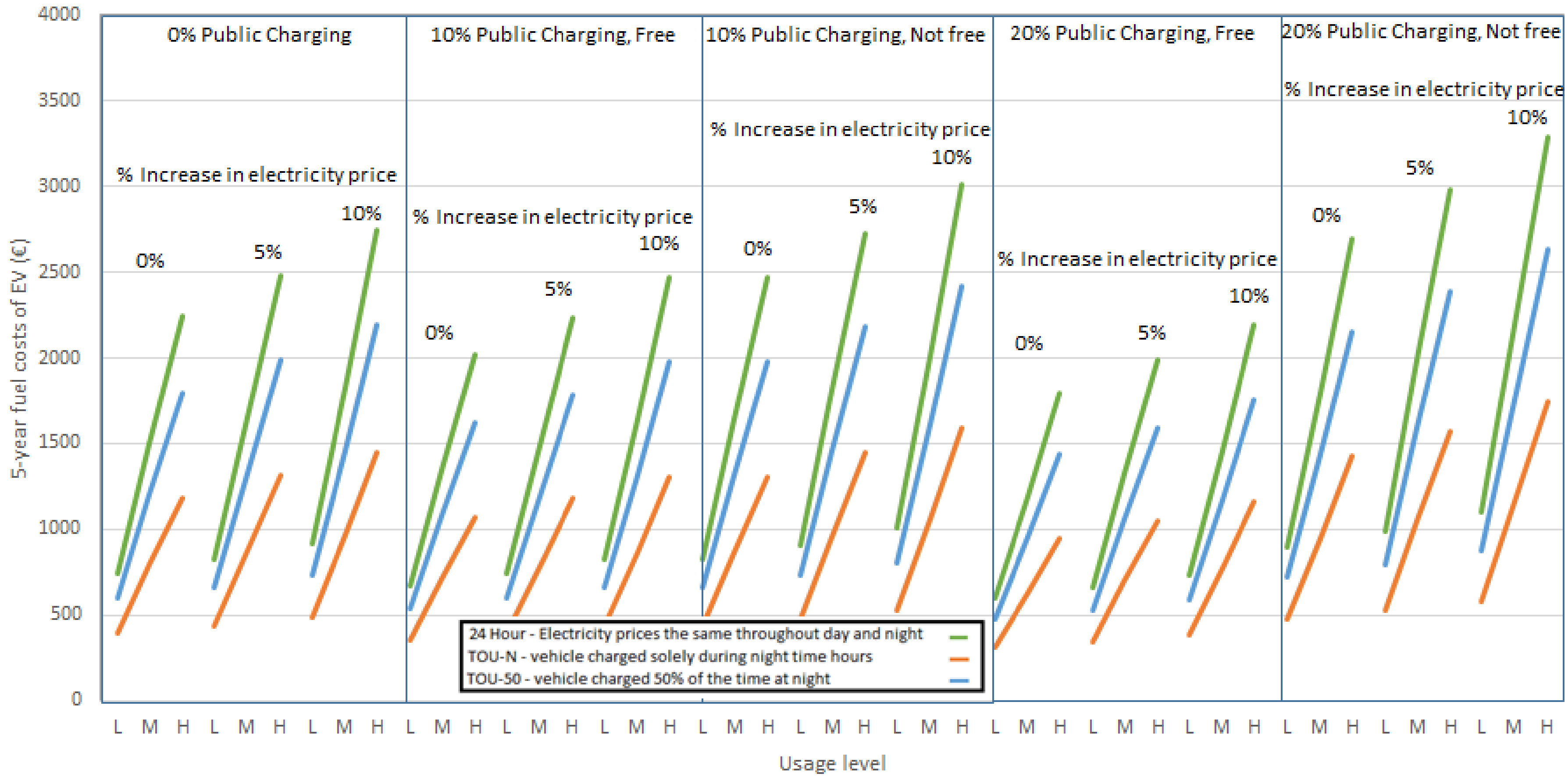


Figure 1 Hierarchical structure of fuel cost scenarios for EVs

RESULTS AND DISCUSSION

Electric Vehicle Fuelling Costs

The five-year fuel costs for the EV for all fuelling scenarios are presented in Figure 2 for domestic electricity pricing. It can initially be seen that the five-year fuel costs vary greatly. The lowest an individual would pay (regardless of the vehicle usage level) is the scenario wherein electricity pricing remains constant (shown as 0% on Figure 2), the individual charges at public locations 20% of the time, public charge points are free-to-use, and charging takes place solely during the night-time hours using a NightSaver plan (i.e. the TOU-N results). The low-usage level result for this scenario is €317 ($371), whilst the high-usage level result is €950 ($1,112). The largest five-year fuel cost for EV charging occurs for the scenario wherein electricity pricing increases 10% per annum (10%), an individual uses public charge points 20% of the time, public charge points are not free-to-use, and the 24 Hour price plan is utilised for charging. The low-usage level result for this scenario is €1,097($1,285), whilst the high-usage level result is €3,290 ($3,854). As such, the largest fuel costs payable by an EV user are over three times the lowest fuel costs, and this difference is primarily dependent on the charging choices an EV user makes (along with the electricity price forecast). A limitation of the work is that potential incentivisation by utility companies through pricing to control when charging takes place is not included in the analysis.



Note: €1 = $1.17

Figure 2 Five-year fuel costs for electric vehicle with domestic electricity pricing

The price plan used by an individual is shown to impact the five-year fuel costs – if an individual charges their vehicle solely during the night-time hours (TOU-N) the fuel costs make up 52.9% of the costs accrued by the 24 Hour plan; if an individual charges at night-time half of the time (TOU-50), the costs make up 80.1% of the costs of the 24 Hour plan. The usage levels of the vehicles are also shown to have a very large effect. Public charging is generally shown to increase the amount an individual pays for charging their vehicle as long as public charge points are not free-to-use. The values in Figure 2 were calculated with respect to domestic electricity pricing; the five-year fuel costs for the industrial electricity pricing are approximately 68.3% of the fuel costs of domestic electricity pricing, with a high-usage minimum value of €649 ($760) and a high-usage maximum value of €2,245 ($2,630).

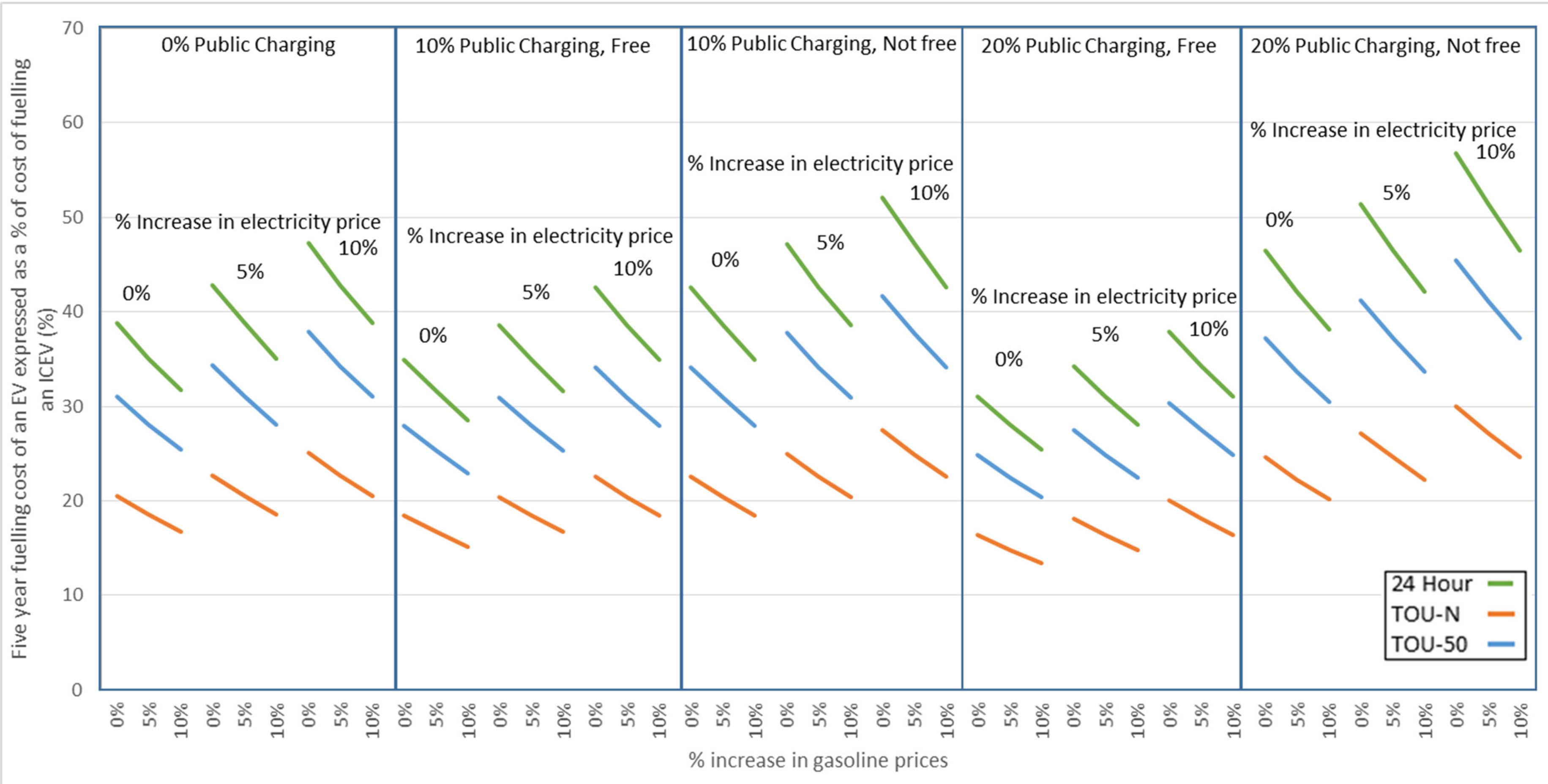
Comparisons to Internal Combustion Engine Vehicle Fuelling Costs

The five-year fuel costs of the ICEV chosen for analysis are presented in Table 1, which can be compared to the EV fuel costs in Figure 2 since the vehicles are of a similar size and usage. The five-year fuel costs are divided into gasoline costs and diesel costs for each of the vehicle usage levels. As expected the fuelling costs of the ICEV are greater than the fuelling costs of the EV. Figure 3 displays the five-year fuelling costs of the EV expressed as a percentage of the fuelling costs of the ICEV for each EV fuelling scenario, with the results pertaining to domestic pricing for the EV and gasoline for the ICEV.

Table 1 Five-year fuel cost for internal combustion engine vehicle

	Gasoline ICEV				Diesel ICEV		
	Low-Usage	**Mid-Usage**	**High-Usage**		**Low-Usage**	**Mid-Usage**	**High-Usage**
Scenario 1 – Constant	€1,930	€3,861	€5,792		€1,779	€3,558	€5,337
Scenario 2 – 5% Increase p.a.	€2,133	€4,267	€6,401		€1,966	€3,932	€5,898
Scenario 3 – 10% Increase p.a.	€2,357	€4,714	€7,072		€2,172	€4,344	€6,517

Note: €1 = $1.17



Note: €1 = $1.17

Figure 3 Five-year fuelling costs of an EV expressed as percentages of fuelling costs of an ICEV [%]

Dependent on the fuel cost scenario, fuelling an EV costs between 13.4% and 56.8% of the cost of fuelling a gasoline ICEV. The percentage savings possible from EV driving are highly dependent on both the electrical energy efficiency of the EV and the gasoline consumption efficiency of the ICEV. The effects of charging during the night-time hours under the NightSaver plan (TOU-N) are also clearly evident in Figure 3, with greater fuel cost savings achieved.

Due to the relative costs of gasoline and diesel, slightly less savings are accruable when comparing a diesel ICEV with an EV under domestic electricity pricing – fuelling an EV costs between 14.6% and 61.6% the costs of fuelling a diesel ICEV. When using industrial pricing, the costs of fuelling an EV are 9.2% -38.8% the costs of fuelling a gasoline ICEV, and in the case of diesel the fuelling costs of an EV are 10% -42% the costs of fuelling an ICEV. It would be expected that the proportional fuel cost savings between EVs and ICEVs would be similar for other vehicle comparisons since the vehicles are of a similar size; however, greater combined monetary savings may be obtained when using a higher-specification EV such as a Tesla Model S *(33)*.

Due to the unpredictability of gasoline and electricity prices, it may additionally be useful to consider a situation in which the costs of gasoline and electricity decrease, and Figure 4 presents the results for this scenario, using a 5% decrease per annum in gasoline and electricity prices. The results in Figure 4 involve domestic electricity pricing and a gasoline-fuelled ICEV. As shown, the results are similar to the proportional costs in Figure 3, with a slight reduction in the costs shown for gasoline for the first three scenarios and a slight increase in the proportional cost for the case where gasoline prices drop by 5%.

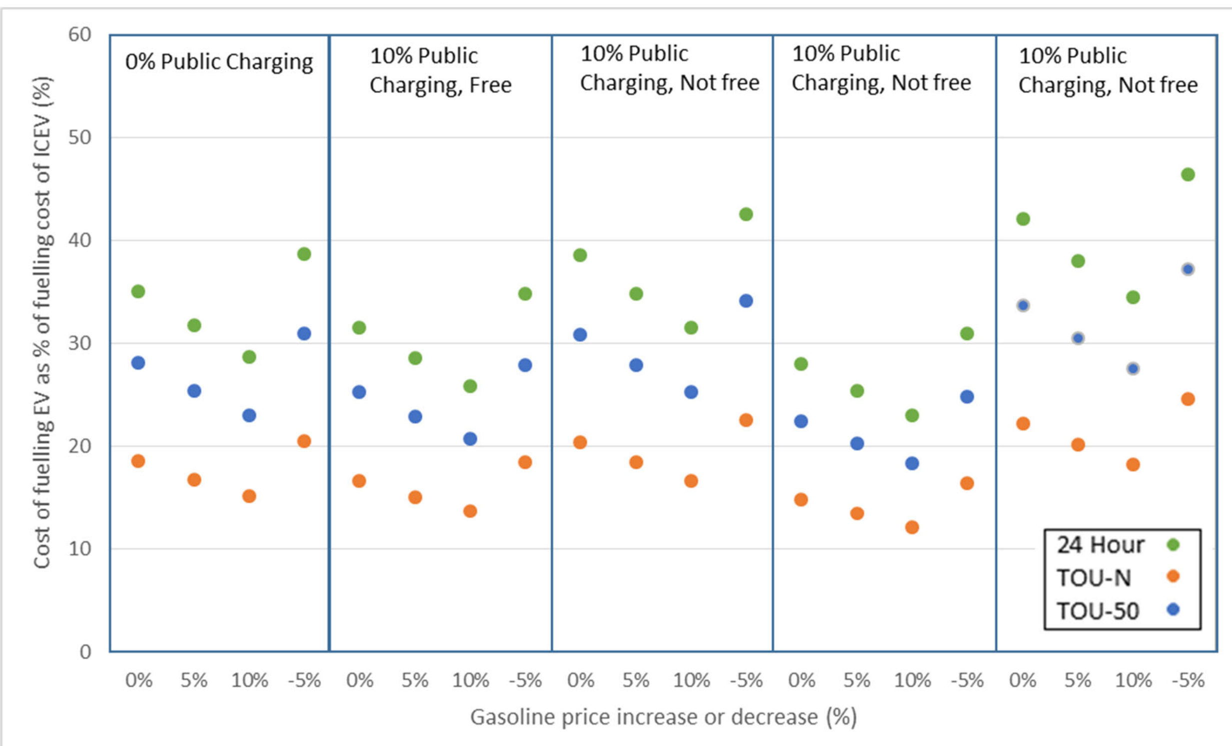


Figure 4 Comparison of EV and ICEV fuelling costs with a decrease in electricity and gasoline prices [%]

Domestic Electricity Bill Increases due to Electric Vehicle Charging

Using data sourced from the CER *(23)*, the increase in the annual cost of electricity in a household as a result of charging an EV can be estimated as a means of informing consumers on potential costs. National average domestic electricity consumption values and their associated annual costs based on the size of a property are displayed in Table 2. The overall annual national average energy consumption quoted by the CER is 5,300 kWh, based on a 3-bedroom household. The various charging scenarios can be applied to these annual electricity bills to determine the relative percentage increases in annual costs due to domestic EV charging. Due to the fact that the data in Table 2 are based on annual household electricity bills, only domestic electricity pricing is considered in the current analysis.

Table 2 Annual national average electricity cost and consumption in Ireland based on property size *(23)*

Size of Property	Total Annual Bill	Total Annual Consumption [kWh]
1 bedroom house	€797	3,100
2 bedroom house	€1,023	4,300
3 bedroom house	€1,211	5,300
4 bedroom house	€1,493	6,800
5 bedroom or detached house	€1,738	8,100

Note: €1 = $1.17

In order to present the results, the scenario of a 5% increase per annum in electricity prices was used and the values in Table 2 were adjusted to account for this, the percentage increases of which are calculated based on the five-year fuelling cost of an EV and the associated five-year electricity bill. The five-year electricity bills for 1, 2, 3, 4, 5 bedroom houses are €4,404 ($5,159), €5,653 ($6,622), €6,692 ($7,839), €8,250($9,664) and €9,604 ($11,250) respectively. The fuelling cost of charging an EV at home under the 5% increase in electricity price scenario is presented in Table 3 and the percentage increases in the five-year electricity bill of a household for each property size when fuelling an EV is added are shown in Figure 5. As shown, larger households are less sensitive to electricity bill increases than smaller households. The positive impact of charging during the night-time hours can again be witnessed in the results.

Table 3 Percentage increases in five-year electricity bill due to EV charging under a Scenario 2 forecast

Five-Year Fuelling Cost of EV at Home under a scenario of a 5% Increase p.a. in electricity price			
Price Plan	**Low-Usage**	**Mid-Usage**	**High-Usage**
24 Hour	€827	€1,654	€2,481
TOU-N	€437	€874	€1,312
TOU-50	€662	€1,324	€1,986

Note: €1 = $1.17

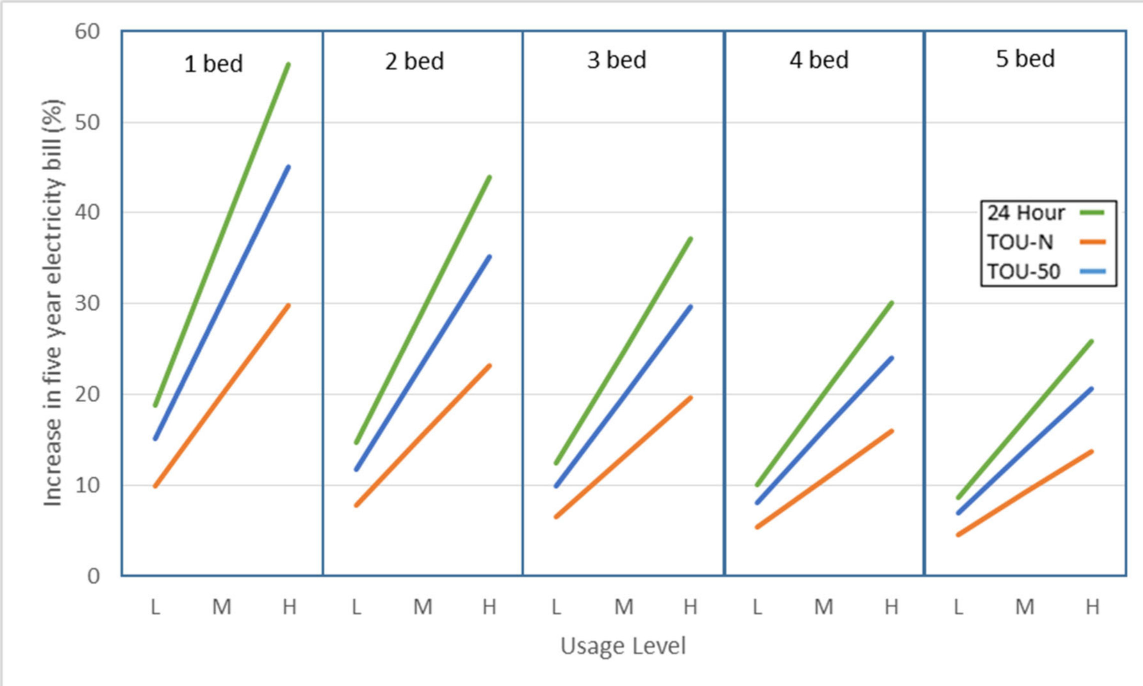


Figure 5 Percentage increase in five-year electricity bill under varying household size scenarios.

Fuelling Costs in Other Countries

The analysis thus far has been presented in an Irish context. Table 4 presents the domestic costs of gasoline and electricity in a number of European countries and in the US *(9,34)*. The costs of gasoline and electricity for all countries apart from Ireland are based on average 2015 prices as these data were the best data available – the costs of gasoline and electricity for Ireland are based on the prices used thus far in the analysis to maintain consistency. Whilst the prices in other countries may have varied since 2015, they nevertheless provide an indication of the potential fuel cost savings associated with EV usage.

Table 4 Fuelling costs in other countries for 2015 ***(9, 34)***

Country	Price of Gasoline [€/L]	Price of Diesel [€/L]	Price of Electricity [€/kWh]	Ratio (Price Electricity/Price Gasoline)	Ratio (Price Electricity/Price Diesel)
Austria	€1.11	€1.02	€0.173	€0.156	0.170
Belgium	€1.30	€1.11	€0.158	€0.122	0.143
Czech Republic	€1.07	€1.03	€0.113	€0.106	0.110
Denmark	€1.46	€1.20	€0.262	€0.179	0.218
Finland	€1.35	€1.16	€0.131	€0.097	0.113
France	€1.25	€1.10	€0.135	€0.108	0.122
Germany	€1.26	€1.03	€0.257	€0.204	0.249
Greece	€1.26	€0.98	€0.153	€0.122	0.156
Hungary	€1.03	€1.02	€0.103	€0.100	0.101
Ireland	**€1.37**	**€1.26**	**€0.166**	**€0.121**	**0.132**
Italy	€1.51	€1.33	€0.199	€0.132	0.150
Luxembourg	€1.07	€0.89	€0.143	€0.134	0.161
Netherlands	€1.53	€1.15	€0.164	€0.107	0.143
Norway	€1.38	€1.27	€0.083	€0.060	0.065
Poland	€0.98	€0.96	€0.125	€0.127	0.130
Portugal	€1.36	€1.10	€0.188	€0.138	0.171
Slovakia	€1.18	€1.99	€0.139	€0.118	0.070
Spain	€1.13	€0.97	€0.212	€0.188	0.219
Sweden	€1.39	€1.30	€0.109	€0.079	0.084
Switzerland	€1.23	€1.27	€0.136	€0.111	0.107
United Kingdom	€1.37	€1.37	€0.167	€0.122	0.122
United States	€0.47	€0.51	€0.081	€0.173	0.159

Note: €1 = $1.17

Within Table 4 two ratios have been calculated – comparing the price of electricity and gasoline, and the price of electricity and diesel. If the ratio values for a country are lower than the ratio value for Ireland (highlighted in bold) then greater fuel cost savings through EV usage are achievable than for Ireland; correspondingly, if the ratio is greater than Ireland's value then less fuel cost savings are possible. The results vary greatly between countries – overall, nine ratios comparing electricity and gasoline are less than Ireland's value whilst twelve are greater, and ten ratios comparing electricity and diesel are below Ireland's value whilst eleven are greater. As the EV fuelling cost scenarios analysed thus far are universal to any country, the results of the comparisons between the countries can be applied to the previous analyses in further determinations of potential fuel cost savings.

Manufacturer-Stated Fuel Consumption vs. Actual Fuel Consumption

The analysis presented in the current study thus far has solely considered the manufacturer-stated fuel consumption rates of the vehicles in order to provide a like-with-like comparison between the EV and ICEV. This section shows how driving style affects the fuel consumption rate of a vehicle and the corresponding fuelling costs associated with the vehicle. During a comprehensive EV trial based in Dublin, Ireland, fifteen Mitsubishi i-Mievs were deployed and data were returned based on the characteristics of trips and of charge events *(20).* The Mitsubishi i-Miev has a manufacturer-stated fuel consumption rate of 135 Wh/km *(35)*; however the data loggers located within the vehicles during the EV trial recorded the energy discharged from the vehicle battery during a trip and the corresponding distance of that trip, allowing the actual energy consumption rate of the vehicle to be calculated. Figure 6 displays the distribution of actual EV energy consumption rates recorded during the EV trial.

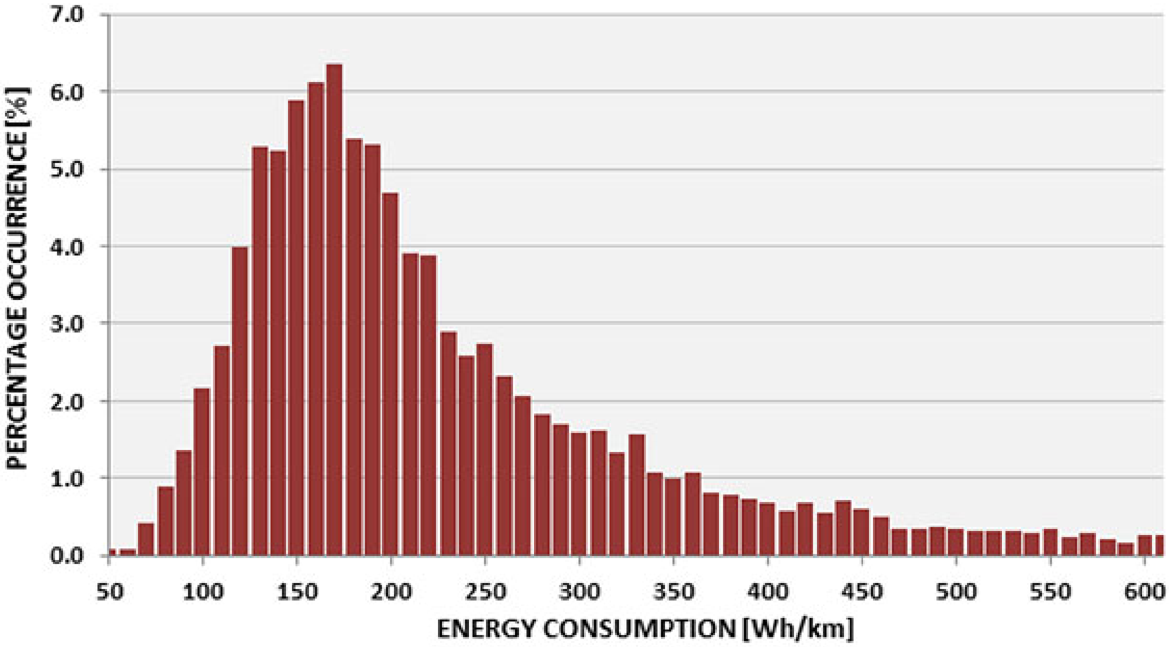


Figure 6 Distribution of actual energy consumption rates recorded during an EV trial

As shown in Figure 6, the distribution of actual energy consumption rates is very dispersed in comparison to the manufacturer-stated value of 135 Wh/km. The peak occurs at the 170 Wh/km band, and the average value is 218 Wh/km with a median of 188 Wh/km. As such, the range of energy consumption rates is very varied but all estimates are greater than the manufacturer-stated value. Dependent on the value considered: if the peak value was used then the fuelling costs would be 1.26 times greater than those reported by the manufacturer; if the median was used then fuelling costs would be 1.39 times greater; and if the average value is used then the costs would be 1.61 times greater than those reported for the Mitsubishi i-Miev.

Public Charge Point Membership Schemes

The final analysis assesses the costs of public charge point membership schemes with respect to their worth to EV users. Some regions and countries price the charging process on a per-charge-event basis, whilst others incorporate membership schemes for unlimited use of the public charging network, such as the Charge Your Car scheme in the United Kingdom which charged a monthly fee of £10 ($13) or an annual fee of £100 ($130) *(11)*. However, it is interesting to look at how the costs of the membership schemes compare with the cost of public charging. In Ireland, a membership scheme was proposed which would charge EV users €16.99 ($19.9) (for unlimited access to standard charge points and an additional charge of 30 cents ($0.35) per minute for fast chargers (as such, a typical 30 minute charge would cost €9 ($10.5)); however the scheme was abandoned due to overwhelmingly negative consumer response and an EV trial is being developed to determine a new membership scheme structure *(12)*.

The analysis conducted in this section is related to the proposed scheme for Ireland. If the monthly fee for standard charge points was €16.99 ($19.9) then a total cost of €1,020 ($1,193) would be accrued for 60 months of membership. Table 5 displays the five-year charging costs solely associated with public charging from the previously conducted analysis. The table is divided into the costs based on the percentage of charge events that take place in public charging locations, i.e. 10% public charging and 20% public charging, and each forecast scenario for electricity is considered. As shown, only one five-year public charging fuel cost result exceeds the €1,020 ($1,193) five-year cost of the membership scheme, which is the scenario with a high vehicle usage level, 20% public charging, and a 10% increase per annum in electricity prices; as such, the membership scheme would not be very economical to an EV user unless they have a high usage level or if they utilise public charging infrastructure to a great extent. Additionally this pricing does not consider the supplementary costs of fast charging which would greatly increase the overall public charging costs. As such it is recommended that future membership schemes take into account these considerations, along with potentially allowing EV consumers to decide costs to pay for membership based on their expected usage of public charging infrastructure.

Table 5 Analysis of effects of membership schemes on the fuelling costs of an EV

Prediction	10% Public Charging				20% Public Charging		
	Low	Mid	High		Low	Mid	High
Scenario 1	150	299	449		299	599	898
Scenario 2	165	331	497		331	662	992
Scenario 3	183	366	548		366	731	1,097

Note: €1 = $1.17

CONCLUSIONS

This study comprehensively investigates the fuelling costs of EVs with a primary focus on the many charging choices available to EV owners with an aim to educate potential vehicle consumers on the contrasting fuel costs associated with each charging option. The comparisons to the fuelling costs of ICEVs reveal EVs as being preferable in all scenarios, although the extent of fuel cost savings are dependent on the choices EV users make with respect to how they fuel their vehicles, with overall average charging costs ranging from between 13.43% and 56.79% the costs of fuelling an ICEV. Higher vehicle usage levels result in greater savings for EVs in comparison to ICEVs, and an increase in the cost of gasoline/diesel inevitably makes EVs a more attractive vehicle option in terms of fuel costs. The results show that fuel cost savings can be accrued through EV ownership in many other countries apart from Ireland, but the savings are dependent on the respective costs of gasoline and electricity in each country. Real data returned from vehicles in an EV trial demonstrate the additional fuelling costs that can be expected by EV owners due to real-world driving conditions, with the median fuel consumption level being 1.39 times greater than the manufacturer-stated fuel consumption rate. It is highly recommended that the differing fuel costs associated with each charging option should be advertised and publicised to a greater extent in order to increase the attractiveness and consumer acceptance of EVs.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Peter Weldon, Margaret O'Mahony; analysis and interpretation of results; Peter Weldon, Patrick Morrissey, Margaret O'Mahony; draft manuscript preparation: Peter Weldon, Margaret O'Mahony. All authors reviewed the results and approved the final version of the manuscript.

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