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Spatial scenarios of potential electric vehicle adopters in Ireland

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Abstract: Transition to electric vehicles is among one public policy to reduce carbon emissions from the transport sector in Ireland. While EV adoption rates are increasing there is broad scepticism about achieving ambitious national policy targets. Using microdata on commuting behaviour and standardised assumptions based on existing literature, we identify candidates that could comfortably satisfy weekly driving needs using an EV without the need to alter behaviour for EV charging purposes. High density areas of potential candidates for transition to EVs are identified, particularly in specific urban areas of Cork and Dublin cities. We also find between 2 to 37% reduction in emissions from car owners based on the different set of assumptions we employ. While the per unit emission reduction in rural areas is higher, the aggregate emission reduction that can be achieved is higher in urban areas because of the higher density of candidates for transition in such areas. The charging infrastructure in these urban areas is already well-developed and marketing campaigns targeting groups such as environmentally conscious younger individuals, who are not often characterised as 'early adopters' in the literature, may pay off in such areas. Public campaigns with a local character in the areas with clusters of the candidates can be more effective in improving the adoption rates.

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1 INTRODUCTION

In Ireland, transportation is the largest energy-consuming sector with a 42% share of final energy consumption and it accounts for 41% of energy related emissions. Passenger transportation is the largest polluter in this sector (SEAI, 2020). In Ireland and in other countries around the world, electrification of the sector is key in the policy agenda to transit towards a more sustainable economy. However, the uptake of this technology has been very slow. Previous literature identifies various individual, technological and infrastructure characteristics which drives the potential adoption of electric vehicles (Zhuge & Shao, 2019; Vassileva & Campillo, 2017; Plötz et al., 2014; Westin et al., 2018). Mukherjee & Ryan (2020) note that the early adopter population in Ireland shows similar characteristics to the ones found elsewhere. Range anxiety and lack of awareness about existing technology and infrastructure can reduce adoption rates of EV technology (Thøgersen & Ebsen, 2019). In this study, we examine the spatial distribution of candidates for a switch to Plug-in Electric Vehicles (PEVs), more specifically Battery Electric Vehicles (BEVs), in the Republic of Ireland using Census data[1]. Based on actual commuting activity data and standardised assumptions on EV distance capability, we define the candidates as those vehicle owners[2] with at least two vehicles and whose existing weekly commuting distances are comfortably within the range capability of a standard BEV battery charge. We assume that these candidates could switch one of their cars to a BEV without adding much hassle/delay to their regular commuting patterns/times and without encountering commonly cited problems of limited range. Further, we expand our analysis by employing the socio-demographic factors which drives the adoption of EVs as identified in the literature.

Our primary objective is to study the distribution of candidates for switching one of their vehicles to an EV and the potential environmental saving from switching. We also extend this analysis to include estimation of gains through emission reduction from that switch and an examination of charging infrastructure network in close proximity to such clusters. Based on the distribution of candidates for switching their second vehicle to an EV as per our various scenarios, we estimate the potential aggregate and average emission savings from each scenario. Globisch et al. (2019) find that proximity to charging infrastructure can improve adoption of EVs among non-traditional adopters. With this aim, we map clusters with close proximity to high density of existing charging infrastructure and in turn identify areas where possible charging network expansion might improve adoption based on the clustering of potential buyers. Understanding the spatial distribution of candidates for switching to BEVs will help in developing local EV targets and thereby help in designing local marketing campaigns associated with specific areas which can localise national promotional campaigns.

Zhuge & Shao (2019) in their study in Beijing, China identify 6 factors which influence the uptake of electric vehicles. They rank the factors according to their relative importance; vehicle price is the most

[1] BEVs are EVs with zero tail pipe emissions unlike hybrid electric vehicles. Furthermore, in this study we are concerned with potential adopters with range anxiety. Range anxiety is not a concern for hybrid vehicle adopters. Hence, in this study we are focusing on the adoption of BEVs.

[2] It should be noted that the unit of analysis in this study is a car owner whose mode of commute is driving their car. The vehicle/s owned can be used by the 'vehicle owner' or 'candidate' for their own transport needs and/or their household's.

important determinant followed by vehicle usage, social network and environmental awareness. The socio-demographic attributes influencing uptake include age, gender, education level, job type, income and number of vehicles. In a study conducted in Denmark, Thøgersen & Ebsen (2019) find that potential adopters are often unaware of or are unconvinced about the technological improvements when it comes to EV technology and availability of charging infrastructure. Guerra & Daziano (2020) note, in their study of potential adopters from Philadelphia, USA, that commuting distances, charging point availability and affordability can be critical in the decision to buy a PEV. Such preferences are also influenced by the residential area and accommodations available, such as parking spots with or without charging infrastructure in urban areas, for each individual. Hence, they argue future studies should incorporate commuting information and proximity to charging infrastructure to correctly identify a household's potential to buy a PEV. Hence in our study we estimate commuting distances using location information from census of Ireland. After considering the range of EVs in Irish market, we assume that a vehicle owner with a smaller commute to work can charge the vehicle once a week and complete all of their travel without worrying about recharging. Hence if their estimated weekly commute distance is below the range of common EVs in the market, we consider them as a candidate for switching their second vehicle based on commuting patterns. By using weekly distance travelled, we are introducing very restrictive distance-based filters in identifying potential buyers thus our analysis is very conservative.

As to the socioeconomic drivers of EV adoption, Haustein & Jensen (2018) in their study in Denmark and Sweden find that BEV owners are typically male, highly educated, have higher incomes and have often more than one car in the household compared to conventional car users. Vassileva & Campillo (2017), in their study in Sweden, find that early EV adopters typically charge their car at home at night. Plötz et al. (2014) find that men who are middle aged and working in technical jobs are some of the early adopters of EV technology in Germany. Westin et al. (2018) note that while socio-demographic variables like gender, age, income, employment, and education level can be associated with early adopter behaviour, when controlled for other factors these associations may disappear. Mukherjee & Ryan (2020) find that EV adopters in Ireland are typically aggregated around the urban areas and have socio-demographic characteristics similar to the early adopters elsewhere. Their study employs micro-data of EV adopters in Ireland to study the spatial distribution of existing EV owners. Based on these studies, we build the profile of candidates for switching to a BEV. Since our study involves only vehicle owners who own more than one car, we do not take gender as a factor in our profile as we assume that the EV purchase decision is a joint decision in a household. Hence, in our more restrictive scenario which considers a socio-economic profile of potential buyers in addition to the distance-based criteria, a candidate for switching their second vehicle is a middle aged, highly educated vehicle owner working in higher income professions, who owns their home and more than one car.

There are studies which previously tried to understand the distribution of potential adopters of EV technology using different data sources (Namdeo et al., 2014; Saarenpää et al., 2016; McCoy & Lyons, 2014). Saarenpää et al. (2016) identify areas favourable for PEV adoption in Finland by mining public data. McCoy & Lyons (2014) employ agent-based modelling to study the diffusion of EV technology in Ireland using survey data. This study emphasises that targeting 'early adopters' for messaging may not result in faster adoption unless detailed network topology is well understood. Namdeo et al. (2014) identify hot spots for expanding the charging infrastructure in urban areas in Northeast England through spatial analysis of the socio-economic characteristics and commuter information of urban residents. Our study adds to this literature by attempting to identify spatial clusters where large number of candidates for switching one of their vehicles to an EV can be found mainly based on commuting distances. Extend of emission reduction is central in the debates surrounding EV adoption, hence we include the estimation of emission reductions which can be achieved by each scenario we design as well.

When it comes to the role played by charging networks in the adoption of EVs, Globisch et al. (2019) note that proximity to EVSE (Electric Vehicle Supply Equipment's) can be critical to a subset of non-traditional adopters. These groups do not belong to the profile of middle aged, male, high income earning early adopters, but are technophilic, environmentally aware younger individuals, mainly women. This sub-group may be residing in apartments or do not own their residences. Hence, they argue that expanding charging infrastructure especially fast charging points may help to speed up the adoption of EVs among non-traditional early adopters. Funke et al. (2019) note that in countries like the Netherlands where the proportion of detached houses is lower, availability of fast charging networks and slow charging networks in public parking spots has reduced the need for home charging infrastructure. In other areas like the US, charging networks are important in metropolitan areas compared to areas with more detached homes (Guerra & Daziano, 2020). Improved quantity and quality of charging infrastructure along with marketing campaigns which reduce misconceptions of EV technology and existing infrastructure can improve adoption in Denmark as per the study by Thøgersen & Ebsen (2019). A majority of Irish households live in detached and semi-detached homes according to the latest census. However, urban areas like Dublin city have a share of 35% of households living in apartments (CSO, Ireland, 2016). Hence in this study we explore the proximity of current charging infrastructure in Ireland to hotspots of candidates for switch to a BEV and study the density of charging points near clusters. Clusters near existing charging infrastructure can be foci for marketing campaigns which target non-traditional early adopters. Expansion of charging networks in existing low-density areas might accelerate the adoption of EVs among population who do not fit the 'early adopter' profile.

The current Irish EV adoption statistics raise significant scepticism about the feasibility of achieving ambitious targets set by Irish government (McAleer, 2019, June 18)[3]. The Irish government plans to increase the number of EVs in Ireland to 1 million by 2030 as per the Climate Action Plan (Govt. of Ireland, 2019). Early reports in 2021 indicate that the popularity of EVs in the Irish market is showing an upward trend (O'Sullivan, 2021, February 23). Our study can identify pockets of geographical areas where a high density of candidates for switching their second vehicle to an EV can be found and targeted for a quick transition to electric vehicles. According to the National Transport Survey of Ireland (CSO, Ireland, 2019), purchase price/ affordability is the main factor influencing the decision to purchase an EV for Irish citizens. The Irish government has already introduced purchase grants, Vehicle Registration Tax

[3] As of 2020, there are 8,473 BEVs registered in Ireland. The current EV adoption statistics for Ireland is shown in table A.1.

(VRT) relief, toll incentives, home charger installation grants and reduced motor tax rates to encourage adoption of EVs (Kevany, 2019). Availability of more charging points away from home and availability of overnight charging at low cost were also factors influencing decision to adopt EV technology as per CSO, Ireland (2019).

While many papers consider the diffusion pathway of EVs and likely early adopters, the current approach differs in two ways. First, we begin from perspective of households' transport needs and the technical capacity of current technology EVs to deliver such service rather than simply focusing on socio-demographic traits and likelihood of EV adoption. Second, we design the analysis to preclude situations where EV range anxiety may be a concern. Hence, within existing commuting/driving requirements and using EV technology currently available on the Irish market, we estimate the technical potential for EVs to comfortably satisfy existing transport needs. This provides an estimate of where existing fossil fuel vehicles can be substituted with EVs without compromise or accommodation in travel patterns. As this estimate ignores factors such as budget constraints or behaviour decisions, following the literature on EV adoption, we drill down to the sub-sample of candidates that are more likely to be early EV adopter based on socio-economic characteristics. This is a more conservative estimate of where existing fossil fuel vehicles can be substituted with EVs without compromise or accommodation in travel patterns. Emission reduction achieved by potential adoption can play an important role in marketing campaigns targeting the more environmentally conscious subgroups. Hence our study includes estimates of emission reductions in the scenarios developed. Lastly, charging networks can be critical in the adoption decisions of non-traditional adopters and hence, we study how the clusters of candidates for switching their existing vehicle intersect with good coverage of existing charging infrastructure.

2 Data and methodology

The analysis in this study utilises the Place of Work, School or College (POWSCAR) data from the Census of population of Ireland 2016 dataset (CSO, Ireland, 2018). The unit of analysis in this study is a candidate for switching their second vehicle to a BEV, whom we assume to be a vehicle owner who commutes by car to work and belongs to a certain subsection of population as per the literature[4]. 39.3% of vehicle owners in the census owns at least one car and drives to work. We do not include car commuters who are passengers in our sample to avoid double counting. The main variables of interest in this study are geographical location of work and home, socio-economic characteristics and vehicle ownership data obtained from POWSCAR dataset along with location information of EV charging infrastructure in Ireland (descriptive statistics shown in table 1).

Data on commuting distance, car ownership and socio-demographic characteristics are employed to identify candidates where EVs can easily accommodate travel needs. For convenience we describe these

[4] We assume that range anxiety is a major concern to a potential adopter who use their car for daily routine journeys compared to someone who uses their car for occasionally journeys. Our analysis provides a conservative estimate due to this restrictive assumption.

as candidates for switching to EVs. Based on these we develop 2 scenarios to identify candidates for switching to a BEV. The number of car commuters (and are also drivers) who belong to each scenario is aggregated to Electoral Division level to study their spatial distribution. Further we estimate emissions savings that can be achieved from switching to EVs based on each of our scenarios. In areas identified as having high EV switching potential, we utilise the information related to charging infrastructure to identify the areas with existing good coverage of charging points and where expansion is needed. The following subsections will explain the assumptions employed in our analysis along with the descriptive statistics of indicators we develop.

2.1 Estimating weekly distance travelled

The POWSCAR dataset includes location data of work and home at Small Area level[5] for each individual. From this information the distance between work and home is calculated. The Euclidean distance between the centroid of Small Area of work and Small Area of home in kilometres is considered as the distance to work. The Euclidean distance is the length of a line segment between two points in Euclidean space (Pebesma, 2018; Karney, 2013). The distance estimation in that case is not an accurate estimation when it comes to the commuting distance because it does not consider route variations, congestion, or other road delays (Sander et al., 2010). Hence, we double the Euclidean distance as commuting distance in our sensitivity analysis scenario. We assume that the real-life scenario will be somewhere closer to the main estimation method or between the main estimation method and sensitivity analysis scenario.

We employ weekly distance travelled instead of daily distance travelled in our analysis. We employ two methods for estimating total weekly distance travelled by the vehicle owner considered. We consider the first method as our main distance estimation method and the second one as our sensitivity analysis estimation method. We estimate work and non-work related travel separately to calculate the total distance travelled in a week. The distance to work is calculated from the Euclidean distance estimation as explained earlier. To estimate non-work related travel, we consider that the average distance travelled by a private car annually in Ireland is 18,000 km for urban areas and 20,000 km for rural areas (CSO, Ireland, 2021). Based on this we estimate that a private car in urban area travels approximately 350 Km per week and a private car in rural area travels around 385 km per week. CSO, Ireland (2021) estimates that only 25% of journeys undertaken by private cars are work related in Ireland. Hence, we add 250 km to urban area weekly journeys and 285 to rural area weekly journeys as distances travelled for non-work related activities in a week[6]. When it comes to total commute to work, we estimate that a typical car commuter

[5] They are the smallest administrative boundaries in Ireland.

[6] Some of the non-work related distances travelled may be pooled in the case of multi-car households with multiple car commuters. In this study we assume that all cars used for commute will travel the same non-work related distances. Hence our distance filter will be providing a more conservative estimate.

might travel 10 times per week to work. We use the following formula to calculate the distance travelled in a week as per the first method.

$$Weekly\ distance\ travelled_h = Distance\ to\ work_h * 10 + Distance\ travelled\ for\ non-work\ related\ activity \quad (1)$$

Further we employ a second method to estimate the weekly distance travelled based on different set of assumptions for checking the sensitivity of our assumptions. In this method, we assume that the Euclidean distance do not completely capture the distance to work and hence double the distance to work to account for traffic and route variations. Average distance to work in the data (as per this assumption) is 34 km. Hence in line with CSO, Ireland calculations of annual mileage of private cars, we add 60 km to distance travelled in a week to urban areas and 120 km to rural areas. To calculate weekly distance in this method, we use the following formula.

$$Weekly\ distance\ travelled_h = Distance\ to\ work_h * 20 + Distance\ travelled\ for\ non-work\ related\ activity \quad (2)$$

In our analysis, the first method, which applies a more conservative assumption on non-work related travel, is considered as the main method and the second method, which applies a more conservative assumption on work related travel, is employed for sensitivity analysis. We take into account the total distance travelled in a week by potential buyers and classify those distances as above or below the range of a typical BEV. The information on distance ranges that electric cars in the market can travel from a single charging session was gathered from various sources including the Sustainable Energy Authority of Ireland (SEAI, 2021). Based on this we calculate the quantiles of distance ranges an EV in market can travel from a single recharge. To determine the cut off range for filtering out possible candidates for switching their second vehicle based on weekly commuting distance, we chose the 25th percentile range as a lower limit and 75th percentile as the upper range limit reached by BEVs in Irish market. The 25th percentile is 310 km and 75th percentile is 436 km as per this calculation. Two of the most popular BEVs in Ireland are Hyundai Kona with a distance range of 449 km and Nissan Leaf with a range of 378 km. Hence our upper range distance calculation is closer to the range of common EVs in Irish market.

2.2 Scenarios for identifying candidates for switching their second vehicle to a BEV

Range anxiety is one of the main reasons for non-adoption of electric vehicles as per the literature (Thøgersen & Ebsen, 2019). If a potential adopter or their household can travel all of their journeys in a week as per above calculations in a single charging session of the EV, we assume that they can easily transition their second vehicle to an EV. It should be noted that the estimate here is highly conservative and most households travel far less distance in a week than we estimate. We devise two scenarios for identifying candidates for switching their second car to a BEV based on two different set of assumptions.

2.2.1 Scenario 1: Commuters with two cars

In the first scenario we employ data on weekly distance travelled and car ownership to study the distribution of candidates for switching their second vehicle (shown in table 2). For identifying the potential buyer population at an ED level, we add the number of car commuters (only drivers counted) in an ED who fulfils the distance criteria and owns two or more cars. Both high and low range mileage attained by the EV's in market are used for the analysis to understand how the hotspots will expand with the improvement of battery technology. As explained earlier we assume that candidates who own more than one car can convert one of their vehicles to a BEV without adding any inconvenience to their existing commuting patterns. About 72.4 % of car commuters who drive to work owns at least 2 cars in Ireland (see table 1). The POWSCAR data does not include information on the main purpose for which each car is used. In some cases, a second car may be used only for occasional journeys such as school runs. In such cases the second car can be transitioned to an EV without worrying about range. Hence the estimate provided in this paper may be a more conservative figure considering the distance based filters applied.

2.2.2 Scenario 2: Commuters with two cars who belong to the socio-economic profile of EV purchaser

In the second scenario we also consider the socio-economic characteristics of the car driver based on literature related to EV adoption (shown in table 2). To avoid counting the same vehicles twice, we only include the individuals within the household who 'drive to work' in our analysis . The census data used for analysis provides information on commuting modes for each unit. The socio-economic characteristics employed in this study includes education, socio-economic group (SEG) which the vehicle owner belong to, home ownership status and age of candidates for switching to a BEV. As per the literature, early adopters of electric cars are highly educated higher income middle aged individuals. Hence in this study we identify such vehicle owners as candidates for switching their second vehicle in our dataset. Managers, employers, lower and higher professionals are coded as high-income individuals in this study [7]. Vehicle owners with a university degree are considered as highly educated for this study. The assigned age group of candidates for switching to a BEV is 35-54. As per literature homeowners of detached homes can install the required charging infrastructure without much hassle and hence home ownership is employed as a determinant of EV adoption in this study. We do not have data on the type of residence in our dataset. Descriptive statistics for categorical variables which are indicators of these socio-economic characteristics which make an individual a candidate for switching their second vehicle to an EV are given in table 1. If a vehicle owner owns 2 or more cars, travels within the battery capability of a typical EV on single recharge in a week, belongs to a higher SEG, have higher educational attainment, is middle aged and owns their home, we consider them as a candidate for switching their second vehicle to an EV. This method is much more restrictive than Scenario 1. We count the number of candidates at ED level. Similar to the first scenario we repeat the analysis by employing weekly distance calculation done via the sensitivity

[7] We do not have access to the data on income of individuals.

analysis method as well and employ scenarios where the preferred EV is low and high range. We do not report the results from sensitivity analysis since they are very close to the main method aggregates.

	Mean	SD
Distance to work (km)	17.7	26.5
Charging point count per ED	1.53	0.91
Charging points within 3 KM (per ED)	12.07	13.87
	Count	Percentage
Candidate SEG (ref. cat: Yes)	535,393	46.3
Candidate education (ref. cat: Yes)	656,500	56.8
Cars owned		
No car	2,990	0.003
1 car	315,641	0.27
More than 1 car	838,828	72.6
Candidate age group (ref. cat: 35-54)	648,527	56.1
Dwelling owned (ref. cat: Yes)	892,348	77.2

Note: Sample size is 1,154,469

Table 1: Descriptive statistics

Conditions applied		Scenario 1		Scenario 2	
		EV range		EV range	
		Low: 310 km	High: 436 km	Low: 310 km	High: 436 km
Distance related (sum less than EV range)	Weekly work commute Distance to work * 10	✓	✓	✓	✓
	Non-work related commute Urban: 250 km	✓	✓	✓	✓
	Rural: 285 km	✓	✓	✓	✓
SEG based (belongs to)	Own 2 or more cars	✓	✓	✓	✓
	Candidate SEG			✓	✓
	Candidate education			✓	✓
	Candidate age group			✓	✓
	Dwelling owned			✓	✓

Table 2: Summary of assumptions employed in the two scenarios of analysis

2.3 Emission reduction achieved from the scenarios

The emission reductions from each scenario are calculated using estimates for recorded emissions per km of travel from petrol and electric cars. Tailpipe emissions per km employed in this study is 130g for conventional/petrol cars and 0 g for electric vehicles. [8] From the weekly commuting distance, the annual emissions estimate for each potential buyer is calculated by aggregating weekly emissions. The aggregate emissions are calculated by taking the sum of emissions from all potential buyers as per each scenario. The aggregate emission from each scenario is calculated by

$$Annual\ aggregate\ emissions = \Sigma_h^H (Weekly\ commute\ distance_h * 52 * Emissions\ per\ km) \quad (3)$$

where h goes from 1 to H, the total number of candidates in each scenario. Weekly commute distances calculated using main method and sensitivity analysis method are separately employed for estimation.

2.4 Distribution of charging point density

We obtain location data on EV charging points across the Ireland installed by the Electricity Supply Board of Ireland. It should be noted that private charging stations which accounts for a smaller proportion of charging points across Ireland are excluded from our analysis. We use geocoded location data on public charging points across Ireland to determine the candidate's proximity to public charging points (ESB, Ireland, 2021). Presence of public charging points or workplace charging infrastructure can be crucial in the decision to buy a BEV for a certain sub-section of population who may not own their homes or live in apartments (Globisch et al., 2019). About 34% of vehicle owners in the dataset works within 3 km of their home, hence we calculate the number of charging points within 3 km of ED centroid to study proximity of candidates to a charging point. We use the topological relations between spatial objects, in this case the number of charging points within 3 km radius of the ED centroid, to estimate the charging point density (see Rigaux et al. (2001); Pebesma (2018); Wickham et al. (2019)). We take snapshots of areas with high density of potential buyers to study how the existing charging networks span within such areas. Since all these areas are urban areas and hence may include large number of renters and individuals who live in apartments, we map the charging point density within 3 km of the home as well in these plots. These maps can highlight areas of high density of potential buyers with or without good charging infrastructure. This analysis will highlight hotspots with existing good charging infrastructure and those which needs more expansion. This can help to accelerate adoption among non-traditional early adopters as explained earlier.

	Scenario 1		Scenario 2	
	Low range	High range	Low range	High range
Count	194,422	481,077	34,670	94,386
Share (%)	16.8	41.6	3.0	8.1

Note: share out of 1,154,469 (Individuals who own at least 1 car and drive to work)

Table 3: Aggregate count of potential buyers

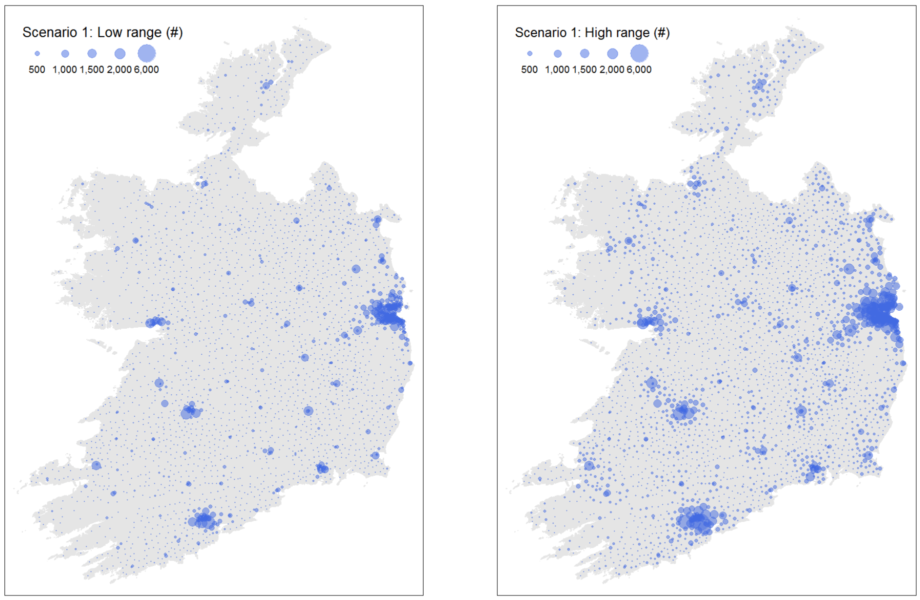

Figure 1: Candidates for switching their second vehicle to a BEV based on Scenario 1 (weekly distance criteria and car ownership)

3 Results

3.1 Distribution of candidates for switch to a BEV based on the scenarios described

The distribution of candidates for switching to a BEV based on commuting distance and ownership of more than one car is studied in the first scenario. The calculation also considers EV battery capacity concerning the distance covered from a single recharge at two levels. We identify hotspots mainly around cities in Ireland where a large concentration of potential buyers is present. Figure 1 shows the distribution of candidates based on these criteria at two different ranges attained by common EVs in market. Based on the lower EV range, i.e. 310km, an estimated 194,000 candidates could comfortably complete their weekly car trips on a single charge. This figure is almost 4 times the number of EVs in the existing car

[8] The generation of electricity implies emissions too (60g per km indirect emissions attributed to electricity generation for electric vehicles (SEAI, n.d.)). However, the reduction emissions in this sector are regulated through the EU Emissions Trading System and not via transportation policies.

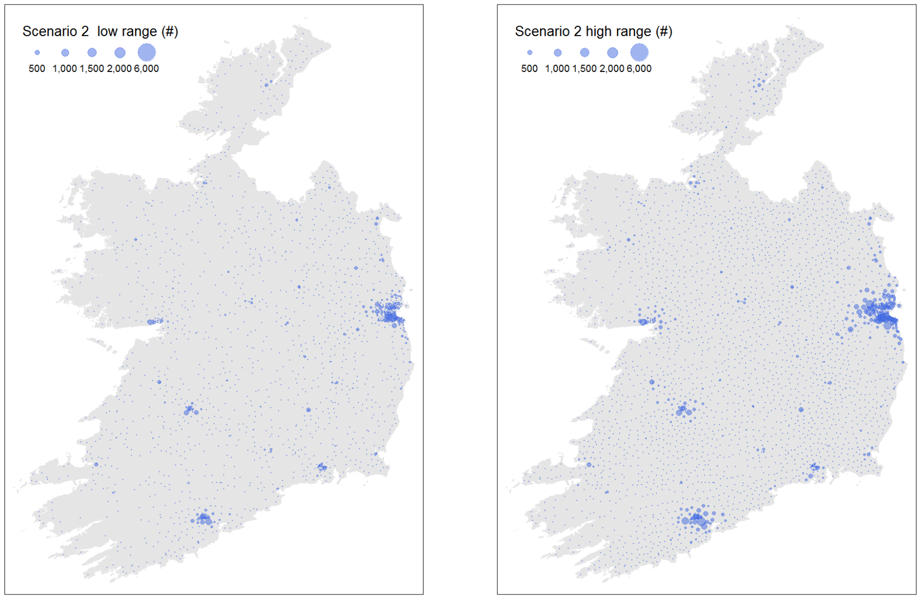

Figure 2: Candidates for switching their second vehicle to a BEV based on scenario 2 (socio-economic characteristics and commuting patterns based on weekly distance calculations)

fleet. Based on a high range EV (i.e. 436km) the number of candidates is 481,000. As mentioned earlier, the calculation is conservative and focuses on vehicle owners with two vehicles so EV range anxiety is not necessarily a factor in occasional longer trips. Table 3 provides the vehicle penetration rate where the base is the total number of vehicle owners who drives to work. Approximately 17 to 42% of vehicle owners could comfortably satisfy existing weekly transport needs on a single charge of an EV. Table A.3 provides a list of high-density areas which are at the 99th percentile or above for aggregate count of potential adopters as per scenario 1. The higher density of potential adopters are found in Dublin, Cork and Limerick counties. Douglas in Cork and Blanchardstown-Blakestown in Fingal have the highest number of candidates for switch to a EVs.

Under scenario 2, where socio-economic characteristics are also considered, we see that the penetration rates for EVs are substantially lower at between 3% and 8% for low and high battery ranges respectively (as per table 3). Similar to Morton et al. (2018) for the UK, we identify potential hot spots for EV substitution in both urban and rural areas. Rural areas with pockets of high density of potential candidates are in Meath, Kilkenny and Kerry. Figure 2 shows the distribution of candidates for EV substitution based on these criteria at two different ranges attained by common EVs in market. The electoral areas with the highest number of candidates for EV substitution are Lucan-Eskar in Dublin, Douglas in Cork and Blanchardtown-Blakestown in Fingal.

		Scenario 1		Scenario 2	
		Low range	high range	low range	high range
Direct emission reduction	Emissions (kt)	367	1073	65.8	213.3
	Share (%)	12.6	36.9	2.2	7.3
	Average (t)	1.88	2.23	1.89	2.26

Note: Emission share out of 2906.72 kt emissions (from 1,154,469 car owners who drive in the sample)

Table 4: Reduction in CO_2 emissions and their share out of total emissions in different scenarios. Values in kilo tonnes (kt) and in %

			Scenario 1		Scenario 2	
		Total emissions (kt)	Low	High	Low	High
Rural	Emissions (kt)	1,156	36.7	362	5.7	67.2
	share (%)		3.2	31.3	0.5	5.8
	Average (t)	2.90	1.98	2.42	1.99	2.45
Urban	Emissions (kt)	1,750	330.4	711.05	60.2	146.2
	share (%)		18.8	40.6	3.4	8.3
	Average (t)	2.30	1.87	2.14	1.88	2.18

Table 5: Emission reduction calculation from various scenarios in rural and urban areas

3.2 Emission reduction potential from switching

The aggregate emissions associated with each scenario is shown in table 4. We provide the results across the two proposed scenarios and EV battery ranges. We estimate aggregate and average potential emission savings from a transition to EV. As per scenario 1 for high range EV the emission savings can be as high as 1073 kt if we consider tailpipe emissions. The first set of rows in table 4 shows that the direct emissions savings range from 2.2% to 36.9% from the emissions generated by vehicle owners who own at least one conventional vehicle. The average emissions in each scenario indicates that improving battery capacity will improve adoption of EVs by drivers of longer distances, which eventually will increase the emission savings further (shown in table 4). We further differentiate emissions from rural and urban areas as well (shown in table 5). The emission savings can be as high as 711 kt in the case of urban areas if we consider only direct emissions or 60.2 kt with more restrictive assumptions. This comes up to a substantial reduction of 40.6% of total emissions from vehicles owners in urban areas. Hence targeting just urban areas for expansion of charging network and messaging in the initial stages can yield significant emission reduction as per our estimation. While urban areas can have the largest environmental savings due to the higher aggregate EV adoption potential as per our scenarios, the average emission in rural areas is higher than urban areas[9]. The average emissions in rural areas are 26% higher than in urban ones (shown in table 5). If we aggregate emission reduction from transition to EV in Dublin county as a whole and Cork county, they jointly account for almost half of the emission reduction which can be achieved (shown in

[9] The average distance travelled by drivers in rural and urban areas are 359 and 317 km as per our estimation.

table A.4). This again shows that targeting the urban areas with hotspots of candidates for messaging can significantly reduce emissions with existing infrastructure.

3.2.1 Charging infrastructure around candidate hotspots

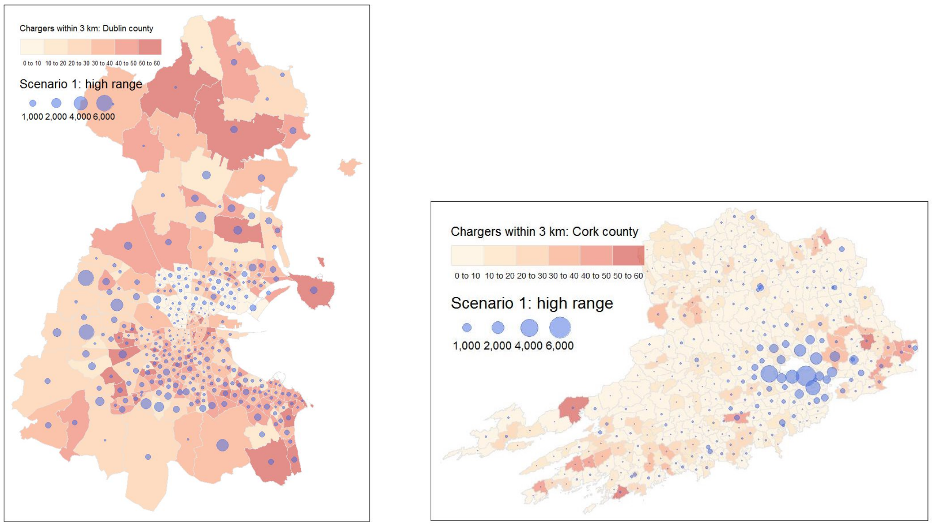

Figure 3: Distribution of candidates for switching their second vehicle to a BEV as per scenario 1 and proximity to charging points in Dublin and Cork

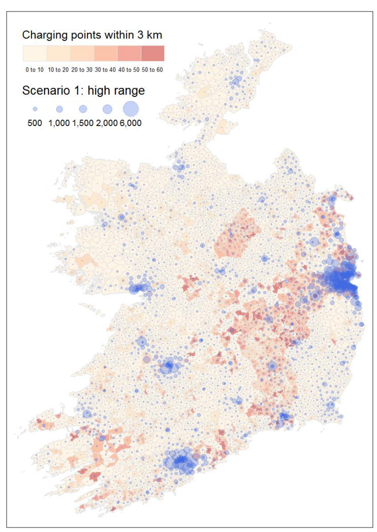

Figure 4: Distribution of candidates for switching their second vehicle to a BEV as per scenario 1 and proximity to charging points in Ireland

Based on the results from previous sections, we zoom into the urban areas with higher density of candidates for switch to a BEV (shown in figure 3). Since the urban area population might be residing in apartments without adequate charging infrastructure, we chart the density of charging points within 3 kms of EDs within these areas. In figure 3 polygons with darker shading shows areas with high density of proximate charging points. Overall charging network in Dublin is better than other areas in the country. Even within Dublin county, there is significant heterogeneity when it comes to density of public EV charging infrastructure. From panel 1 in plot 3 there are areas with high density of candidates with lower density of charging infrastructure. However, considering the existing infrastructure within Dublin, non-traditional early adopter categories can be targeted for messaging related to EVs. Urban areas other than Dublin lack the density of charging infrastructure compared to Dublin, for example in Cork county as shown in panel 2 of figure 3. Overall charger density in Ireland with distribution of candidates for switch to a BEV is shown in figure 4. Targeted expansion of public charging networks in Cork, Limerick and Galway can attract non-traditional early adopters of EV.

4 CONCLUSION

The Climate Action Plan of Government of Ireland sets out ambitious targets for EV adoption in Ireland (Govt. of Ireland, 2019). However, the current EV adoption figures raise significant scepticism about achieving these targets. By using microdata on commuting behaviour and standardised assumptions based on existing literature, we identify the candidates for the switch to BEVs and compute the potential emission savings from such a switch. We find that there are between 194,422 and 481,077 cases where EVs could be substituted for internal combustion engine vehicles and comfortably satisfy weekly driving needs without the need to alter behaviour. This shows the potential which can be reached by targeting a wider population based on their commuting patterns rather than just the groups who are considered traditionally as 'early adopters' for messaging related to EV adoption. If we narrow down the candidates for substitution based on their fit to the profile of an early adopter as well, those figures drop dramatically to between 35,000 and 94,000. This therefore reflect the depth of challenge to reach policy targets. However, this still implies that the current number of 8,473 BEVs in Irish market could be at least 4 times larger.

Affordability is the main factor influencing the decision to purchase an EV for Irish citizens (CSO, Ireland, 2019). There are already several financial incentives to overcome such barriers, including purchase grants, Vehicle Registration Tax (VRT) relief, toll incentives, home charger installation grants and reduced motor tax rates. This research identifies geographical areas with a high density of potential candidates for switching their second vehicle to an EV. Such information is beneficial for targeted or localised promotion of EVs. While high level marketing of EV transition is necessary the identified hotspots where targeted or specialised efforts to encourage EV uptake might be most successful. Specialised initiatives could be established in these areas in addition to existing incentives. For example, local EV test drive centres, sponsored local EV champions, etc can be organised in such areas. The research identifies locations in Dublin, Cork and Limerick as core areas (i.e. hot spots) where there is potential for greater diffusion of EVs. These locations are identified as having a high density of residents that can easily satisfy their weekly travel needs based on a single battery charge, in essence without range anxiety concerns. The analysis focuses on multi-car owners, with the assumption that one car is potentially replaced with an EV. Range anxiety is often associated with occasional longer trips so for longer trips multi-car owners are not constrained to use their EV. In summary, the assumptions underlying the analysis are such that the potential EV switchers can continue all their usual travel patterns without any concerns regarding finding public EV charging points or delays there.

A significant reduction in transport emissions is feasible from switching to EVs. Many of the hot spots for EV switching in our scenarios are situated in urban areas. Emission savings associated with a single EV are relatively small but aggregate emission savings potential within such areas is substantial. While switching to an EV is a private decision for each vehicle owner and their household, the promotion of the collective emission reduction potential could be used as a motivation for more environmentally conscious groups to consider adoption of EVs.

Availability of charging points away from home and availability of overnight charging at low cost are also factors influencing decision to adopt EV technology as per CSO, Ireland (2019). The distribution of current charging stations infrastructure in certain hotspots such as County Dublin is already extensive. Hence such areas can be targeted for campaigns aiming for improving adoption rates among non-traditional adopters of EVs, like environmentally conscious younger individuals or apartment dwellers. Other urban areas such as county Cork could gain from improvements in charging infrastructure especially near areas with clusters of candidates. In areas where there are fewer detached houses, Dutch-style free parking incentives coupled with expanded slow charging network in public parking areas can be an effective policy to accelerate adoption (Globisch et al., 2019). Campaigns that target the identified hotspots could create a multiplier effect because drivers are more likely to adopt EVs as EV adoption becomes normalised (Noppers et al., 2019).

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Appendix A I

Vehicle type	Total fleet	Private cars
Petrol/ diesel and electric hybrids (HEV)	48,683	45,167
Electric (BEV)	9,120	8,473
Plugin hybrids (PHEV)	6,427	6,305

Table A.1: Electric vehicle fleet in Ireland as of 2019 (Department of Transport, Tourism and Sport, 2019)

	Sensitivity analysis			
	Scenario 1		Scenario 2	
	Low range	High range	Low range	High range
Count	378,269	487,948	71,987	95,865
Share (%)	32.7	42.2	6.2	8.3

Note: share out of 1,154,469 (car owners who are drivers)

Table A.2: Aggregate count of potential buyers as per the sensitivity analysis scenario

	ED	County	Scenario 1 high range
1	Blanchardstown-Blakestown	Fingal	5,553
2	Douglas	Cork County	5,335
3	Lucan-Esker	South Dublin	5,269
4	Ballincollig	Cork County	3,740
5	Castleknock-Knockmaroon	Fingal	3,360
6	Glencullen	Dún Laoghaire-Rathdown	3,126
7	Ballycummin	Limerick City and County	2,954
8	Carrigaline	Cork County	2,808
9	Swords-Forrest	Fingal	2,545
10	Bearna	Galway City	2,495
11	Naas Urban	Kildare	2,482
12	Firhouse Village	South Dublin	2,397
13	Lehenagh	Cork County	2,340
14	Celbridge	Kildare	2,334
15	Leixlip	Kildare	2,287
16	Ennis Rural	Clare	2,242
17	Ballysimon	Limerick City and County	2,221
18	Kilkenny Rural	Kilkenny	2,114
19	Firhouse-Ballycullen	South Dublin	2,037
20	Navan Rural	Meath	2,025
21	Caherlag	Cork County	1,840
22	Rathcooney (Part Rural)	Cork County	1,808
23	Tallaght-Jobstown	South Dublin	1,791
24	Dunboyne	Meath	1,735
25	Kilmacanoge	Wicklow	1,724
26	Tralee Rural	Kerry	1,688
27	Maynooth	Kildare	1,570
28	Lucan-St. Helen's	South Dublin	1,569
29	Ballybaan	Galway City	1,560
30	Swords-Lissenhall	Fingal	1,523
31	Kinsaley	Fingal	1,469
32	Donaghmore	Meath	1,429
33	Tramore	Waterford City and County	1,425
34	Morristownbiller	Kildare	1,423
35	Ashtown A	Dublin City	1,405

Table A.3: EDs with 99 percentile count for potential adopters as per Scenario 1 high range

County	Emission reduction Direct (kt)	
	Scenario 1	Scenario 2
Cork County	127.4	26.8
South Dublin	84.7	17.5
Fingal	82.05	18
Dublin City	76.1	15
Dun-Laoghaire Rathdown	61.2	17.6
Kildare	52.9	10.9
Limerick City	45.4	8.9
Galway County	41.8	9.4
Meath	40.1	7
Kerry	32.5	5.7
Tipperary	32.4	5.2
Wexford	31.4	5
Clare	30.3	6
Waterford City	29.2	6.1
Donegal	29.1	5.2
Mayo	28.2	4.7
Wicklow	26.7	5.4
Kilkenny	25.3	4.9
Louth	23.7	4.3
Cork City	23.6	4
Westmeath	17.9	3.3
Galway City	16.5	3.5
Sligo	16.1	3.6
Laois	15.9	2.5
Cavan	15.8	2.3
Roscommon	14.5	2.5
Offaly	14.3	2.2
Monaghan	13.8	1.9
Carlow	10.9	1.8
Longford	7.1	1.1
Leitrim	6.1	1.1

Table A.4: County wise tailpipe emission reduction in each scenario considering a high range EV being adopted

		Sensitivity analysis			
		Scenario 1		Scenario 2	
		Low range	high range	low range	high range
Direct emission reduction	Emissions (kt)	452	725	88.8	148.4
	Share (%)	15.5	24.9	3.05	5.1
	Average (t)	1.19	1.48	1.23	1.54

Note: Emission share out of 2,906.72 kt emissions (from 1,154,469 car owners who are drivers in the sample)

Table A.5: Reduction in CO_2 emissions and their share out of total emissions in different sensitivity analysis scenarios. Values in kilo tonnes (kt) and in %