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A Framework to Measure Regional Disparities in Battery Electric Vehicle Diffusion in Ireland

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A framework to measure regional disparities in battery electric vehicle diffusion in Ireland

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Abstract: This work studies the role of socio-economic and geospatial factors in shaping battery electric vehicle adoption for the case study of Ireland. It provides new insights on the level and timing of likely adoption at scale using a Bass diffusion model combined with a spatial model. The Bass model demonstrates that a country like Ireland may experience peak sales between 2025 and 2030 given current trends, reaching overall uptake levels that are not commensurate with current policy goals, whilst also potentially creating gulfs in regional take-up. The key conclusion from the spatial analysis is that location matters for uptake, through various channels that help or hinder adoption such as resources, information, and policy. Additional investment in public charging infrastructure facilities may also be needed as gaps in coverage exist, especially in rural areas to the West and South-West of the country. Although Ireland enjoys good network coverage overall, this study suggests that more charge points may be needed in some counties and Dublin city and suburbia where the number of charge points is currently disproportionate to a minimum network coverage comparable with the land area, population size, number of private vehicle owners, and travel behaviour. As the urgency for climate action intensifies in the coming decade, our spatio-temporal approach to studying uptake will not only help meet Ireland's socio-ecological vision for the future, but also provide insights and strategies for comparable countries that are similarly placed in terms of electric vehicle adoption.

Keywords: Battery electric vehicle adoption, spatial analysis, consumer behaviour, Bass diffusion model, Ireland

JEL Classification: D1, D9, O3, Q4

Highlights:

- Battery electric vehicle sales are poised to peak between 2025 and 2030 in Ireland given current trends.
- As the market for electric vehicles matures, evolving adopter profiles must be accounted for.
- Regional disparities in uptake could delay progress with policy implementation.
- Positioning the role of space in policy design will facilitate more effective policy making.
- Designing spatially aware policies could escalate adoption faster than current trends allow.

1. Introduction

Societal trends such as decarbonisation, digitalisation, and the energy transition have opened up new markets for residential renewable energy technologies (RETs). Decarbonisation policy goals are driving governments to push electric vehicle (EV) uptake in the mobility sector (IEA, 2021a). EVs are more efficient than internal combustion engine vehicles (ICEVs) and have already reached cost parity for some models (U.S. Department of Energy, 2021).[1] Widespread integration of EVs will be crucial as whilst most sectors are transitioning to cleaner energy, transport still accounts for a growing share of emissions worldwide (European Commission, 2016). Although EVs are considered zero emission at their point of use, their true environmental impact is dependent on the electricity generation mix used to fuel these vehicles and there are also emissions associated with battery manufacture (Hill et al., 2019). However, several life cycle assessments have demonstrated that EVs are better for the environment overall, including a study by the International Council on Clean Transportation (ICCT) that suggests that an EV's higher manufacturing-phase emissions would be paid back in two years from manufacture, unlike ICEVs which will emit emissions for life (Hall and Lutsey, 2018; Maarten Messagie, 2017).

In a recent report outlining 400 target milestones for governments in the transition to net zero emissions by 2050, the International Energy Agency (IEA) recommended phasing out of new ICEVs from 2035 and decarbonising global electricity generation by 2040 (IEA, 2021b). The ICCT has also called for annual targets for EV market penetration starting in 2025 (Mock, 2021). This is because lowering CO_2 earlier will enhance cumulative emission savings for society and ensure a smoother technology uptake in advance of meeting global 2050 emissions targets. Many countries have implemented a 2025-30 ban of all new ICEVs, for example, across Europe (Ireland by 2030, France by 2025, Netherlands by 2030, Norway by 2025, Sweden by 2030, UK by 2035) and in the Americas (Costa Rica by 2021) (Wappelhorst and Cui, 2020).

Studies have shown that the rates of uptake of new environmental technologies that are cost-effective often remain low due to market failures such as inadequate information, agency and

[1] The Kia Niro hybrid introduced in 2021 will cover 10.1 miles for £1 of petrol. The electric Kia e-Niro will cover 33.1 miles for a £1 of electricity. A comparable diesel SUV - NISSAN Qashqai - will cover 10.3 miles for £1 of diesel. Based on these fuel economy figures, there is an incentive already for consumers to purchase pure electric.

split incentives problems, high consumer discount rates leading to present bias, network externalities, and lack of access to credit markets (Jaffe et al., 2005; Popp et al., 2009; Shiferaw et al., 2015). Understanding the current level of diffusion, especially compared with policy goals, and identifying the motivations behind consumer uptake will enable policymakers to create better regulation and incentive structures to enable faster diffusion of EVs (OECD, 2019). Previous research has studied the motives for consumer uptake quite extensively and has identified that the current incentives are not aligned with consumer preferences in terms of both the ability and willingness to pay for new BEVs for a vast majority of consumers (Mukherjee, 2020; Mukherjee et al., 2020; Mukherjee and Ryan, 2020). In this study, we aim to enrich our understanding of the possible reasons behind the failure of current policy incentives to boost uptake thus far. We explore diffusion in some depth for the case of Ireland using Bass's theory as a simple, intuitive and widely used model of innovation diffusion and expand our analysis to include the role of space in terms of rural/urban location, as well as regional socio-economic disparities and variations in public charging infrastructure coverage (Bass, 1969).[2]

Research has shown that the risk of exposure to environmental pollution and climate change affects individual regions and groups differently (Ganzleben and Kazmierczak, 2020; Shao et al., 2021). Policies, such as those geared towards encouraging EV adoption, can also have distributional consequences in the way they favour certain socioeconomic groups over others, often subsidising the wealthy, thus undermining their goal of improving inclusivity (Canepa et al., 2019; Miller, 2018; Nguyen, 2020). Studies have further shown that wealth tends to cluster in regions and is typically skewed in favour of urban areas (Young, 2013). The adoption of BEVs also has a prominent network effect in that an adopter gains additional value as more people adopt BEVs due to the interdependence between BEV adoption and charging station investment (Li et al., 2017). The Bass model provides an ideal framework for analysing overall BEV take-up as it allows for such network effects and there are several studies that have applied this model to EV sales data in other countries (Ayyadi and Maaroufi, 2018; Brdulak et al., 2021; Ensslen et al., 2019; Islam, 2014; Li et al., 2020). However, it does not facilitate a granular understanding of the individual factors that shaped the outcome. Crucially, using the

[2] Urban clusters have a minimum of 5,000 inhabitants plus a population density of at least 300 people per square kilometre (km^2). A rural community has fewer than 5,000 inhabitants.

Bass model alone masks any regional disparities in uptake as it presents only an aggregate-level outlook.

We therefore also chose to study the geographical relationship between charging infrastructure rollout and uptake, as this has been repeatedly identified as a key concern and in some cases the biggest driver of uptake along with the spatial dynamics between regional wealth and BEV uptake (Foley et al., 2020; Neaimeh et al., 2017; Sierzchula et al., 2014). Although the influence of *individual* wealth has been researched extensively, in particular providing overwhelming evidence for the fact that higher incomes raise the propensity of uptake, the relationship between charging infrastructure, *regional* wealth and uptake geography has not yet received the attention it deserves (Bauer et al., 2021; Brückmann and Bernauer, 2020). Thus, the case for studying regional wealth is made here as it acknowledges how social factors such as peer effects may compound spatial factors to influence the uptake of new technologies in the way they reinforce certain behaviours and norms that are predominant within a social group nested within a certain geographical location (Tóth et al., 2021).[3]

In Ireland, total transport emissions increased by more than 23% between 1990 and 2018, remaining the most energy-consuming sector with a 42% share of final energy consumption and accounting for 41% of energy-related emissions (SEAI, 2020). These figures call for a rapid overhaul of Ireland's transportation system. In this regard, Ireland already has a progressive target of reaching nearly 1 million EVs on the road by 2030 allowing a mix of hybrid electric vehicles (HEVs), plugin hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) (United Nations Secretariat, 2019).

To facilitate this transition, a maximum grant of €5,000 has been in place since 2011 for qualifying privately purchased EVs to ease credit constraints (Kevany, 2019). This subsidy is now applicable to both BEVs and PHEVs with a list price of over €14,000 but no longer to

[3] Higher passive and active peer effects have been observed primarily for rooftop solar PV adoption but social contagion occurs frequently for most types of RET adoption. Passive peer effects are a result of observing the presence or use of a technology in an individual's immediate vicinity, whereas active peer effects propagate via interpersonal communication channels such as with members of a social network. Both the neighbourhood and the social network would largely consist of individuals from a similar socio-economic background having shared expectations of acceptable behaviour and comparable social aspirations (Currier, 2016; Davey-rothwell et al., 2016; Dulin et al., 2018; Fleckman et al., 2019; Friedrichs and Blasius, 2003; Schultz et al., 2009).

HEVs (SEAI, 2021). A reduced toll fee was also announced until 2022 for BEVs and PHEVs (IEVOA, 2021a). Moreover, the maximum grant for PHEVs has been capped at €2,500 since July 2021, giving a slight edge to BEVs which have no tail pipe CO_2 emissions compared with around 60g/km of CO_2 for PHEVs (Department of Transport, 2021). In addition, BEVs receive Vehicle Registration Tax (VRT) exemption separately to the grant support. Motor tax for BEVs is also currently discounted at €120 per annum and is typically €170 per annum for PHEVs. Both the VRT and motor tax are calculated based on direct CO_2 emission values. Despite providing these incentives for the purchase of BEVs, consumer uptake of BEVs in Ireland has remained historically low, creating a mismatch between ambition and reality (Mukherjee and Ryan, 2020; O'Neill et al., 2019). As of May 2021, there were over 100,000 hybrid cars, and around 30,000 EVs (including both passenger and commercial vehicles) on the road, with BEVs and PHEVs each at ~15,000 (CSO, 2021a). This compares poorly with a national vehicle fleet size of ~2.5m, of which passenger vehicles claim the lion's share at ~2.2m (Department of Transport Tourism and Sport, 2021).

Thus, the main contribution of this research is that it extends the Bass model analysis of BEV uptake by examining regional socio-economic and infrastructural disparities using geographical information systems (GIS) analysis in conjunction with the diffusion framework, to mirror real-world policy constraints. It is highly likely that national policies are less effective when localised social influences are ignored (Heidrich et al., 2017). We propose here some policy interventions based on possible channels of influence in sub-national uptake levels that address regional divides in resource allocation. These, if left unattended, could have serious ramifications for balanced regional development and the achievement of Ireland's national emissions targets as we continue to transition away from fossil fuel technologies in the face of the climate crisis.

The rest of the paper is structured as follows. Section 2 describes the data and methodology used for our unique spatio-temporal approach to modelling diffusion. Section 3 presents the results and discussion. Finally, Section 4 concludes with insights for the design and implementation of future transportation policy.

2. Data and methods

Irish BEV sales data from the Central Statistics Office (CSO), public charging infrastructure locations from the *ecars* division of the Electricity Supply Board (ESB), and a comprehensive measure of regional deprivation, the Pobal HP Deprivation Index, available in the public domain on the EU Open Data Portal, as well as proprietary adopter location data from the Sustainable Energy Authority of Ireland (SEAI) and the Electricity Supply Board Networks (ESBN), are used in this analysis. This section presents these key data sources, the Bass diffusion model, and the spatial analyses used in this paper.

2.1 Data

BEV sales data for Ireland is published monthly since 2015 by the CSO (CSO, 2021a). Figure 1 plots quarterly data for the number of new private BEVs licensed for the first time in Ireland between January 2015 and May 2021. Figure 2 plots the cumulative sales and demonstrates that, although passenger BEV sales have been rising steadily over time, sales have only taken off since 2018, rising from under 600 BEVs sold in 2015 to about 2000 in 2018. However, the steepest rise has occurred between 2018 and 2021 with the industry recording almost 14,000 BEVs on the road by the second quarter of 2021. BEVs still constituted a mere 1.8% or 13,774 out of 763,700 new vehicles licensed for the first time between the first quarter of 2015 and May 2021, as Figure 3 illustrates.

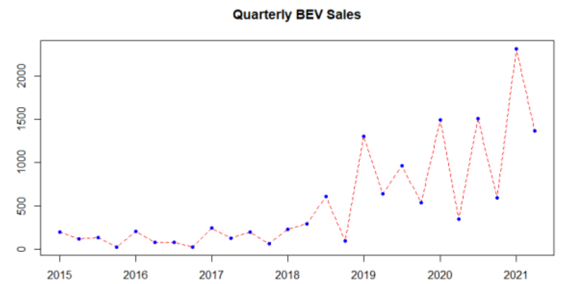


Figure 1 Quarterly BEV Sales, Ireland, Jan. 2015-May 2021. *Source: CSO*

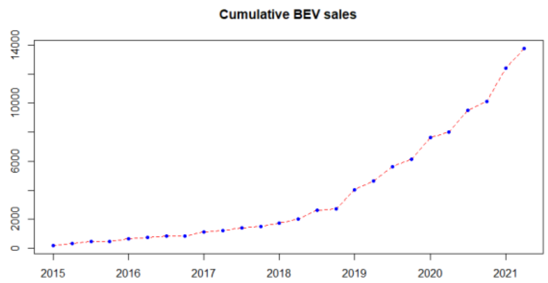


Figure 2 Cumulative BEV Sales, Ireland, Jan. 2015-May 2021. *Source: CSO*

We received locational data for all residential BEV registrations in Ireland since January 2018 up to November 2020 from the SEAI based on their allocation of grants for the installation of home chargers. We had previously received comparable residential adopter data from the ESBN for home chargers registered with them up until August 2017. Dropping the observations that relate to commercial EV ownership in a third dataset from the CSO that contains complete

EV ownership data (both residential and commercial) without geolocations, the discrepancy between the complete dataset and the two charge point datasets combined is about 1500 observations, which could partly be explained by the ownership of second EVs (therefore having no new charge point installation associated with those purchases) and partly by the data we are missing for the last quarter of 2017.

Moreover, whilst 95% of the small area codes were present in the SEAI dataset, the small area code did not match the address at county or town level for about 35% of cases. Even if an address mapped to small areas correctly, in some cases it might have been the dealer address or a business address. There were also probable issues around second homes and mismatches between meter point reference numbers and Eircodes, mostly in typical "holiday home" counties and Dublin, implying that chargers could have been installed at second homes.[4] We were, therefore, compelled to drop a further 2000 data points due to incomplete or problematic locational information. Our final dataset contains geolocations for 6490 BEV adopters. The accuracy of the mapping of county information to small area codes for the grants data that we have is about 80%. While it is certainly usable and is the best data we could procure given the General Data Protection Regulation, we are aware of the need for caution with our adopter location data.[5]

[4] Eircode is a national postcode system in Ireland launched in 2014 which assigns a unique seven-character postcode for each address.

[5] The General Data Protection Regulation 2016/679 is a regulation in EU law on data protection and privacy in the European Union and the European Economic Area which also addresses the transfer of personal data outside the EU and EEA areas.

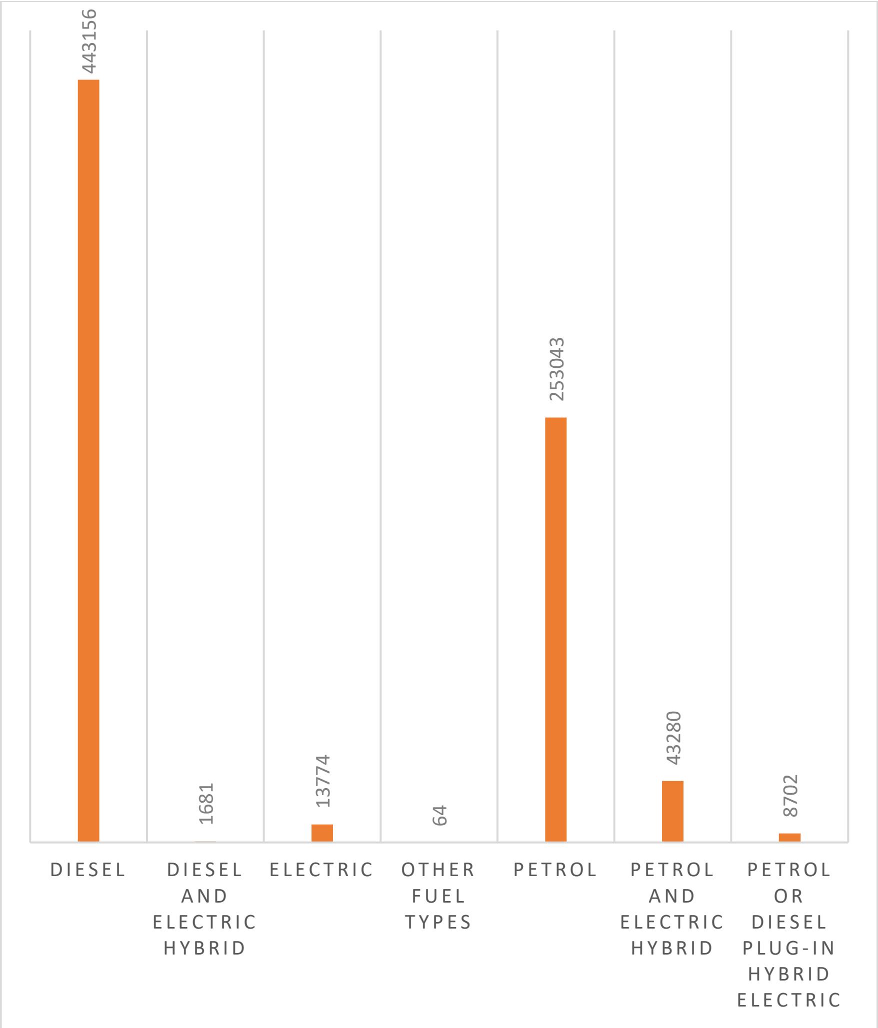


Figure 3 New private vehicles licensed for the first time between January 2015 and May 2021 by type. *Source: CSO*

Spatially, the distribution of BEV adopters appears to be concentrated around the two largest cities in Ireland – Dublin and Cork - both in absolute numbers and when normalized by population, and this has been maintained over time, as represented in Figures 4 and 5.

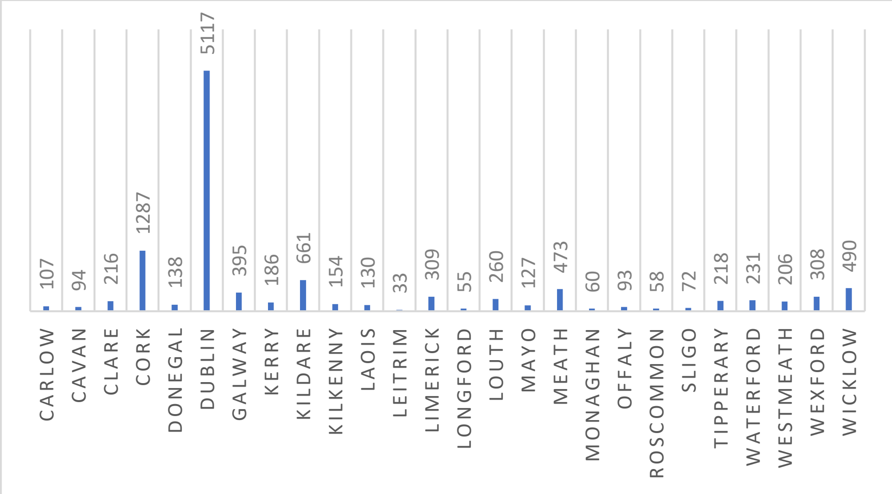


Figure 4 Adopter count by County (cumulative figures up to November 2020). *Source: CSO*

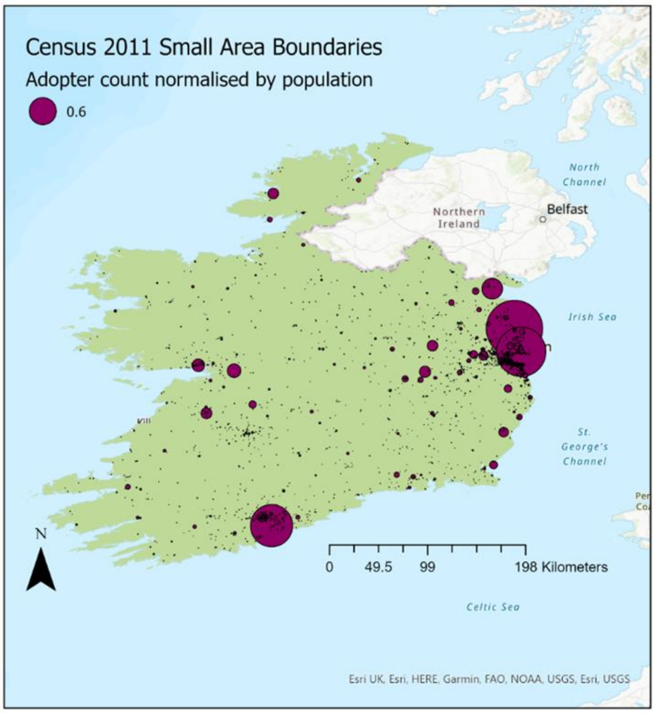


Figure 5 Proportionality diagram of cumulative BEV adopter counts normalized by population by small area boundaries in Ireland, November 2020. *Source: SEAI*

We used the publicly available ESB *ecars* dataset on public charge point locations in Ireland of which there are currently 900+ available nationwide in locations such as on-street, shopping centres, and car parks (ESB ecars, 2021). There is at least one charge point in every town with 1500 or more inhabitants. Fast charge points are located every 50km on all major inter-urban routes at service stations and roadside cafes to cater for long-distance drivers. We successfully geocoded 772 charge points out of the 865 that had locational information attached on the map.

Figure 6 displays a proportionality diagram showing the relatively even distribution of these charging stations across the Irish landscape.

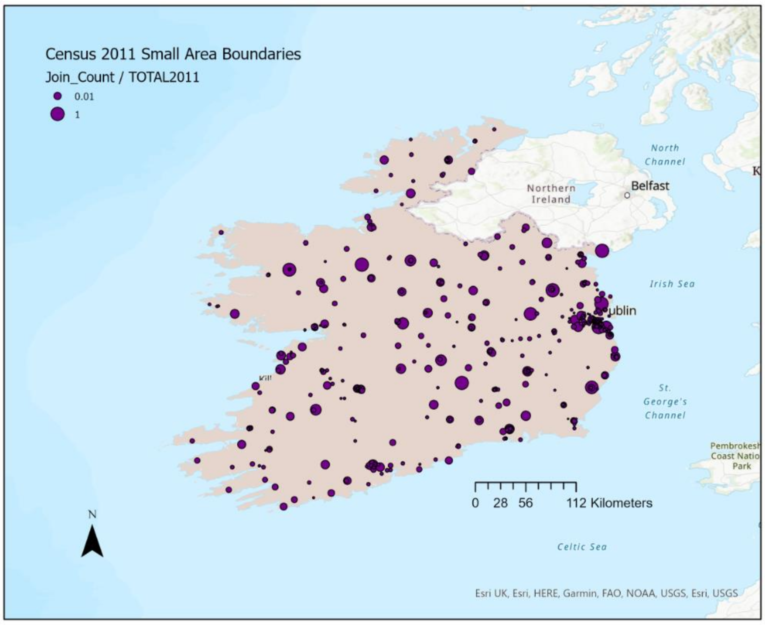


Figure 6 Proportionality diagram of *ESB ecars* public charge point locations in Ireland.

Source: ESBN

Finally, due to the unavailability of granular income data from the CSO, we used the 2016 Pobal HP Deprivation Index as a proxy measure for poverty levels (Pobal, 2017).[6] The index is based on the combination of three dimensions of relative affluence and deprivation: demographic profile, social class composition and labour market situation, and provides a more comprehensive vantage point of relative deprivation than crude income figures do alone (Calleary and Minister for Rural and Community Development, 2021). The index has been employed in transport planning in Ireland in the past for road networks and rural public transport, for instance, but not for driving EV policy yet (Haase, 2018). Figure 7 provides the range of values across counties showing a mean index of -5.24. For context, the index ranges from -10.79 to 6.14 for Ireland, with cities having higher values and therefore faring better than

[6] This index data is calculated as the Electoral Division (ED) level aggregates from the 2006 and 2011 Census Small Area level data, which are available from http://maps.pobal.ie/. The Absolute Index Scores have a mean of zero and a standard deviation of ten in 2006, with varying means and standard deviations in 2011 and 2016 that reflect the underlying trends. For more information on index construction see http://trutzhaase.eu/services/hp_deprivation_index/. The 2016 data associated with the 2016 census wave is the latest available for Ireland.

rural areas on average. Figure 8 maps this data. Dublin and its surrounding counties of Wicklow, Kildare, and Meath, as well as County Cork appear to be relatively affluent. Levels of affluence also vary within Dublin County, with Dún Laoghaire-Rathdown County providing a sharp contrast to South Dublin County, the latter being relatively disadvantaged (although not normally considered a deprived area) despite its proximity to the most affluent neighbourhood in Ireland.

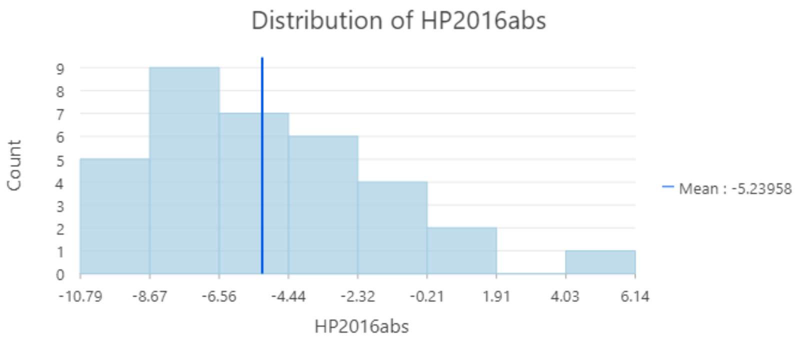


Figure 7 Frequency plot of the 2016 Pobal HP Deprivation Index (absolute figures) across counties in Ireland. *Source: Pobal Maps*

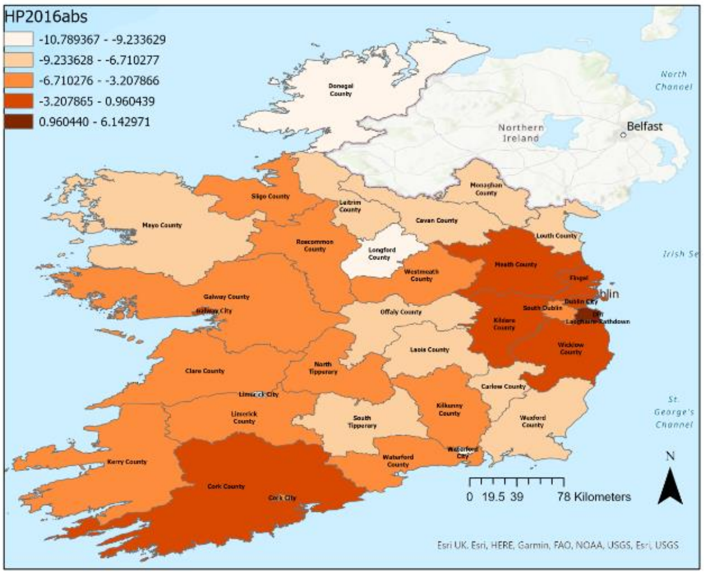


Figure 8 Choropleth map showing relative levels of deprivation at county level in Ireland. *Source: Pobal Maps*

2.2 Methods

Bass (1969) proposed a diffusion framework that highlighted the importance that innovators and imitators have in shaping the market penetration rate of a new technology into society (Bass, 1969). Innovators are defined as individuals who adopt new technologies independently of others within a social system, whilst imitators are influenced by the adoption of new technologies through pressures from the social system. This framework uses a conceptually appealing and mathematically elegant structure to present a rationale of how current and potential adopters of a new product interact to create the conditions for an innovation to diffuse through a target population of customers. It has become one of the most cited models in the diffusion literature having applications in marketing, strategy, technology management and other fields (Bass, 2004). We apply this model here to position Irish BEV sales on the diffusion curve, and thereby estimate a temporal specification for potential peak sales. The insights are applicable to other early adopter markets for BEVs that want to predict their longer-term adoption trajectories. The model was built using R version 4.0.3 (R Core Team, 2020).

Spatial analysis has also gained traction in recent years in the technology diffusion literature due to a growing recognition of the joint role that common temporal and spatial exposures play in explaining varying levels of uptake (Comin et al., 2012; Leibowicz et al., 2016; Lengyel et al., 2020; Morton et al., 2015). Coincidentally, although Irish EV policy has been critiqued as being too ambitious given current incentives and adoption rates, there has been no network analysis of the complementarity between BEV use and charging infrastructure provision to the best of our knowledge. There is also little understanding of regional socio-economic influences in BEV uptake in Ireland. The relevance of these factors in shaping future policy prompted this work to fill this gap. All spatial analyses were conducted using ArcGIS Pro (Esri Inc., 2020). The Bass diffusion model and the spatial analysis frameworks used are described in turn in the sections below.

2.2.1 The Bass diffusion model

Several mathematical models exist that help predict the rate and pattern of technology diffusion which have essentially evolved from biological principles. When a species interacts with its limiting environment and other species, inter-species competition results in the dominance of the new species and/or some change in the species mix. Similarly, a newly launched innovation proceeds to compete for market shares resulting in either a displacement of old technologies or a plurality of technologies with altered market shares. In either case, the market is finite and imposes constraints on growth both in terms of resources for production and final demand for products. The result is a classic *S*-shaped trajectory with a clear saturation point when usage stabilises, rather than an exponential growth process.

$$\frac{dN_i}{dt} = \alpha_i N_i - \frac{1}{\gamma_i}\sum_{j=1}^{n}\lambda_{ij}N_iN_j\,, \quad i = 1, \dots \dots, n \tag{1}$$

At its most general form, the diffusion process is defined by a system of differential equations, the Lotka-Volterra equation [*Eq.(1)*], where the growth of a product *i* is a function of the density of the product N_i and its interactions with other products. The interactions, in turn, depend on the density of individual products N_i *and* N_j and the collision rate λ_{ij} between products, where α_i and γ_i are constants. When an innovation is a better fit in terms of its technological, economic, and social characteristics, it replaces existing ones. Some derived functional forms that have found applications in the economic geography literature in areas such as human population growth and technological forecasting include the logistic function, positively skewed S-curves, the Gompertz function and the modified exponential function (Tjørve and Tjørve, 2017; Vandermee, 2010; Verberk, 2011). However, most models are a variation of the logistic curve as is the Bass model.

The Bass model uses three parameters based on observed sales – an innovation coefficient (*p*), an imitation coefficient (*q*) and the market potential (*m*) – to forecast diffusion patterns.[7] Innovators play a bigger role at the start of diffusion. However, both innovators and imitators make initial purchases, and as such, the difference in their purchase behaviour has less to do with timing and more to do with what influenced their purchase decision.

$$\frac{F'(t)}{1 - F(t)} = p + qF(t), \quad F(0) = 0 \tag{2}$$

The model solves the ordinary differential equation specified in *Eq.(2)*, where the expression on the left-hand side is the adoption rate of a product at time *t*, assuming no purchase so far.

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}}, \quad p > 0, \; q > 0 \tag{3}$$

Solving by separation of variables, the cumulative diffusion as a function of time is represented by *F(t)* as in *Eq.(3)*, where *p* is the innovation coefficient and *q* is the imitation coefficient.

[7] A product is successful when $q>p>0$. While *p* is generally smaller than 0.1, *q* is not larger than 1. When *m* is normalised by the total population, it is bounded within [0,1]. During a product life cycle, there are *m* initial purchases. *m* could be larger than 1 for some products, if a consumer owns two units, for instance. For products with longer life cycles, such as EVs, this is less likely to hold true, and *m* is closer to the level of total purchases.

$$f(t) = m\frac{(p+q)^2}{p}\frac{e^{-(p+q)t}}{\left(1+\frac{q}{p}e^{-(p+q)t}\right)^2}\,,\quad p>0,\qquad q>0\,,\qquad f(t)=F'(t) \tag{4}$$

The first derivative of the cumulative function, *f(t)*, represents diffusion at a specific point in time *t*, as represented in *Eq.(4)*.

$$\lim_{t\to\infty} f(t) = K,\ \ K>0,\ \ -\infty < K < \infty \tag{5}$$

$$\lim_{t\to-\infty} f(t) = 0 \tag{6}$$

As $t \to \infty$, *f(t)* reaches an upper limit, *K*, the level at which growth saturates. *Eq.(5)* and *Eq.(6)* denote the limiting functions.

$$t_{peak} = \frac{\ln\left(\frac{q}{p}\right)}{p+q},\quad p>0,\quad q>0 \tag{7}$$

$$\frac{d^2f}{dt^2}\left(t_{peak}\right) = 0 \tag{8}$$

The time of peak sales or the inflection point is represented by *Eq.(7)*. t_{peak} must meet the condition specified in *Eq.(8)*.

$$f\left(t_{peak}-t\right) = f\left(t_{peak}+t\right) \tag{9}$$

$$y_{peak} \coloneqq f\left(t_{peak}\right) = \frac{K}{2} \tag{10}$$

A curve is symmetric around t_{peak} if the condition in *Eq.(9)* is met and a necessary condition for symmetry is represented in *Eq.(10)*.

$$\Delta t = t_{90} - t_{10}\quad where\quad f\left(t_p\right) = \tfrac{p}{100}K,\quad 0<p<100 \tag{11}$$

Finally, Δt in *Eq.(11)* denotes the length of time needed to grow from 10% of *K* to 90% of *K*.

$$s_t = a + bS_{t-1} + cS_{t-1}^2 \tag{12}$$

$$m = \frac{-b \pm \sqrt{b^2-4ac}}{2c} \tag{13}$$

$$p = \frac{a}{m} \tag{14}$$

$$q = b + \frac{a}{m} \tag{15}$$

If s_t represents the per period sales at time *t* and S_{t-1} represents cumulative sales lagged one period, $s_t = mf(t)\ and\ S_t = mF(t)$. We substitute these terms in *Eq.(2)* to arrive at *Eq.(12-15)*. Bass models can be fit by both linear and non-linear least squares algorithms for parameter estimation, depending on whether growth and substitution functions have been linearly transformed or not. We fit a linear regression model of s_t on S_{t-1} and S_{t-1} squared to estimate the model, as denoted in *Eq.(12). a* represents the intercept while *b* and *c* represent the slope coefficients, which we combine to compute *m, p* and *q* as in *Eq.(13-15).*

The Bass model is still a simplified model that uses a plausible number of parameters and restrictive assumptions to make predictions of future sales and therefore has limitations that have prompted several extensions and modifications to reflect real world phenomena better (Horvat et al., 2020; Lee and Huh, 2017; Liu et al., 2013).[8] Nevertheless, the model is useful as it provides a satisfactory fit for our historical empirical data and adequately explains the process of how BEVs are getting adopted in the Irish population. We recognise however that future uptake in Ireland may not be as accurately predictable as the underlying parameters are sensitive to global trends, policy changes and technological developments, which have been continuous and fast moving for BEV technology.

2.2.2 Spatial analysis

BEV adoption is inherently geospatially heterogeneous. We used several GIS tools to unearth spatial relationships in our data. This includes data visualisation tools such as bivariate plots and choropleth maps, and two specific geoprocessing tools from the ArcGIS analysis and network analyst toolset, namely, buffer ring analysis and closest facility network analysis. The following section provides brief descriptions of these geoprocessing tools.

The buffer ring analysis was employed to generate multiple simplified Euclidean buffer polygons at specified distances around the input features, in this case BEV adopters.[9] These

[8] These simplifications are as follows: the market potential volume is a constant during a product's life cycle, diffusion does not depend on other competing and complementary innovations, the technology does not change over time, geographic boundaries are unimportant, the influence of marketing does not change during the diffusion process, no supply restrictions are assumed, only the first purchase of a product is considered, thus repeated purchases are not modelled, and finally, the model is symmetric, implying that the maximum rate of diffusion cannot occur after the product has gained 50% of market share. In reality, the relative evolution of market shares is important as prices and advertising change. Products may also be abandoned in favour of new product generations, and thus, the cumulative number of adopters does not rise monotonically. Products are also introduced at varying times in different markets, and word-of-mouth communication occurs between geographical neighbours. Moreover, diffusion patterns are not always symmetric.

[9] Euclidean buffers measure distance in a two-dimensional Cartesian plane where straight-line distances are calculated between two points on a flat surface. These are more commonly used than the geodesic buffers (that

buffers were merged and dissolved using the buffer distance values to create nonoverlapping buffers. Since the input features used a projected coordinate system – the IRENET95 Irish Transverse Mercator projection - planar buffers were produced in the output (OSi, 2021a). The IRENET95 Irish Transverse Mercator projection is suitable for proximity analyses in small areas because the distortion in the map is small enough to be unnoticeable (Cory et al., 2001). The Transverse Mercator projection has also been identified as the most suitable type of map projection by Ordnance Survey Ireland (OSi), which is the national mapping organisation responsible for the surveying and mapping of Ireland, because it is orthomorphic, implying that the relative local angles about a point on the map are shown correctly and the local scale around any one point is constant, such that the shape of small features is maintained.

The closest facility network analyst tool (available with an ArcGIS Pro Network Analyst license) models the movement of small automobiles, in this case BEVs, and finds solutions that optimize in real time the travel time or travel distance between 'incident sites' and 'facilities', depending on the cost variable chosen. We used the tool to measure the cost of traveling from BEV adopters to their nearest public charge points by choosing to optimise the distance travelled (rather than time). We wanted to find multiple nearest charging facilities with a direction of travel going from adopters towards public chargers. The travel mode used the network hierarchy built into the analysis to help with long distance routing and generalised the output geometry by 10 metres to reduce the computation time. Moreover, certain restrictions were imposed on the network data source. The driver used a standard passenger vehicle (to simulate the experience of a BEV driver), and avoided carpool roads, express lanes, gates, and private and unpaved roads. Roads under construction and through traffic were prohibited. In addition, travel obeyed one-way roads, avoided illegal turns, and followed other rules that were specific to cars. U turns were allowed in dead ends and intersections when traveling between locations. Choosing time as a cost variable would have required the use of dynamic travel speeds based on a specified start time and live traffic data to generate accurate analysis results. Since we did not have access to live traffic data, we deferred this analysis to future work when this data becomes available and utilised the tool with the distance optimisation alone.

preserve the shape of the earth in distance calculations) and are suitable for analysing distances around features in a projected coordinate system that are concentrated in a relatively small area.

3. Results and discussion

This section presents an application of the Bass model to Irish BEV sales and insights from a spatial analysis of the data.

3.1 Trends in Irish BEV sales: Bass model results

Figure 9 plots actual and predicted sales for the period of observed sales, i.e., January 2015-May 2021. The somewhat more jagged curve represents the actual sales and incorporates seasonal effects and the introduction of new models that are not part of the Bass model specification. The smoother curve represents fitted or predicted sales. Figure 10 illustrates actual and predicted sales rolled forward to future periods, up to the year 2040.[10] The model endogenously determines that at current uptake rates, a peak market potential *m* of 32,513 BEVs (corresponding to $p \approx 0008$ and $q = 0.19$ in the model) will be reached between 2025 and 2030 after which growth in sales will decline very rapidly to near zero having had a cumulative lifetime product sales of 32,513. Note that this figure only encompasses new private BEVs licenced in Ireland for the first time and does not include second hand or other imported vehicles registered abroad.

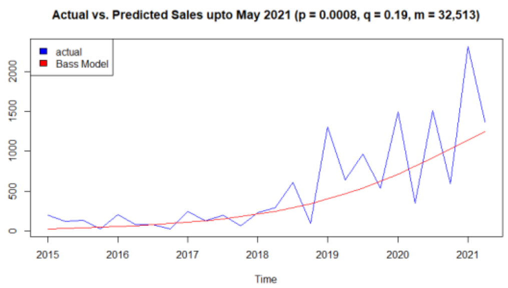


Figure 9 Actual vs. Predicted annual BEV Sales, Ireland, 2015-21. *Source: CSO*

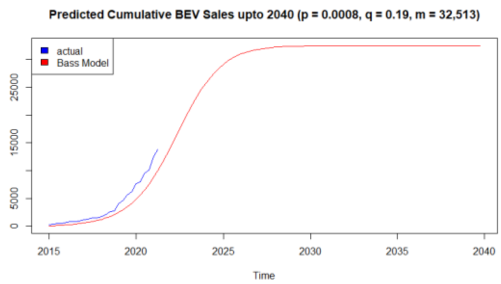


Figure 10 Predicted Cumulative BEV Sales, Ireland, 2015-40. *Source: CSO*

This figure provides a stark contrast to a value of *m* based on ownership levels of private cars in Ireland which currently stands at 444 per 1000 inhabitants. For a population of 4.9m then, there are currently around 2.2m private cars in the country. Assuming a constant growth rate

[10] We chose 2040 as our end point as many world leaders have committed to achieving ambitious climate targets by 2040.

of 2% per year up to 2040, there will be around 3.2m private cars by 2040.[11] This could potentially be a theoretical maximum market potential that assumes market penetration of BEVs will be at 100%, implying that every private passenger car driver eventually switches to a BEV. The model results are lower than this target by a factor of approximately 1,000. This means that at current BEV uptake rates, technology characteristics, and policy, this level of market penetration is not achievable without further government intervention. Importantly, not achieving it will negate any possibility to meet the European Green Deal's targets for sustainable transport which seeks a 90% reduction in greenhouse gas emissions by 2050 (Mathieu, 2020). Hence, alternative pathways to diffusion will need to be considered in addition to market based approaches, at least in the short term.

The Bass model provides some useful insights to determine a way forward. However, the shape of the diffusion curve is sensitive to model parameters. The value of the market potential, *m,* linearly scales the diffusion curve. If *m* rises, the time of peak sales moves to the right but any potential intervention that aims to influence and manage this market potential must be able to influence the values of both *p* and *q.* This is because innovators have the biggest influence on uptake after product launch: the larger the value of *p*, the faster will be the initial diffusion. Additionally, the initial speed of adoption influences the timing of peak sales: a slow start will create a peak later in time. In contrast, imitators have the biggest influence on the height of the peak: a higher value of *q* will generate a higher (and earlier) sales peak. In general, higher values of both *p* and *q* will result in faster and larger diffusion. Thus, harnessing this social effect could drive BEV adoption to a point on the curve when driving an ICEV becomes socially unacceptable and mass adoption becomes unavoidable due to social norms that favour BEVs. Figure 11 illustrates this process for higher values of *m, p* and *q* based on published estimates found in the automotive technology literature (Massiani and Gohs, 2015).

[11] The Irish passenger car market has seen a very modest average yearly increase of ~1.4% in uptake in the past decade, with recent years recording a marked decline in sales compared with previous years (Statista, 2021). Although European passenger vehicle demand is expected to plateau for the foreseeable future, sales could grow slightly in the near future due to various factors, for instance, the COVID-19 pandemic could increase personal vehicle user uptake in order to reduce the risks of using shared mobility options, population growth and economic recovery could increase the overall demand for private vehicles, and population demographics could be changing in favour of those preferring personal vehicles for convenience or out of necessity (CEIC, 2021; Hensley et al., 2021; Matthew Nitch Smith, 2016; Metz, 2007; Winton, 2021). Therefore, we assume a slightly higher growth rate of 2% in our calculations to allow for any unexpected surge in demand.

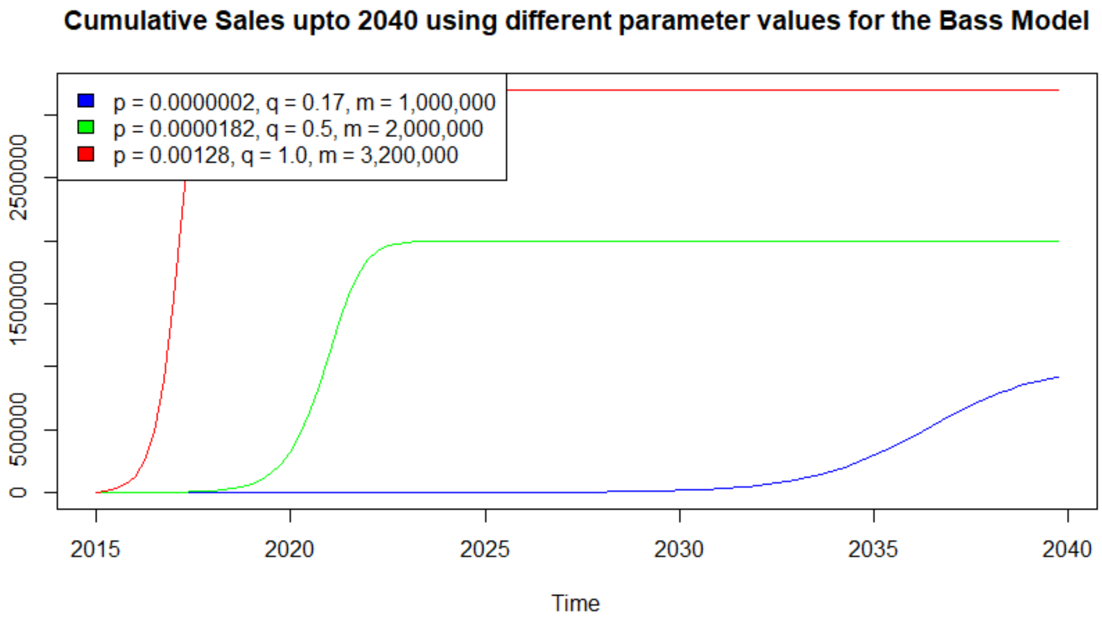


Figure 11 Cumulative BEV Sales using different parameter values for the Bass Model, Ireland, 2015-40. *Source: CSO*

Nevertheless, the next decade will undoubtedly see major changes in the automotive industry whereby all elements of the BEV supply chain align and scale up together, such as raw materials for batteries, motor production, battery production, car production, and infrastructure for charging. These developments will alter the underlying diffusion parameters for BEVs again and potentially move Ireland towards mainstream adoption of BEVs irrespective of new policy choices if these changes contribute to higher estimates of p, q and m than those estimated from historical data in the model, although the exact trajectory is yet unknown.

A global and national policy shift towards banning of ICEVs from 2030, major VRT changes in 2021 in Ireland in favour of BEVs, rapid technological development and industrialisation of the battery manufacturing process, more competitive prices and other market dynamics may be very different to historical trends. This could mean that BEVs will overwhelm ICEVs in due course as they ride the exponential growth phase in accordance with the natural learning process. Some of these changes are happening already and 2021 has seen an unforeseen rise in EV sales compared with previous years. EVs comprised over 13% of new cars licenced for the first time in Ireland in the first half of 2021 compared with 6% over the same period in 2020 (CSO, 2021a). Thus, out of all new car sales, the share of BEVs and PHEVs combined has more than doubled in a year. This sort of progress, if sustained, may place Ireland well on track to meet at least 20% of new car sales with EVs by 2023 and about 30% by 2030, which is close to the 2030 national target of realising 1m EVs on the road.

3.2 GIS analysis: outcomes and insights

Although the demand forecasting exercise above tells us something useful about the likely timing of peak BEV sales, it essentially provides a macro-level picture by smoothing out the vagaries of human behaviour, and the dynamics of technologies, economic impacts, and social influences across regions. Thus, the Bass model alone cannot explain the driving forces behind the evolutionary process manifest in the data. We provide more granular insights here into the overall uptake levels for Ireland, de-composed into regional trends using CSO Census Boundaries (CSO, 2011). Ignoring regional disparities would not only be detrimental to the uptake of national policies but also inefficient, as opportunities for better policy design and a more equitable distribution of resources could be missed.

Relative affluence and BEV adoption

Affluence appears to be correlated with BEV uptake as determined by the differences identified in previous research on the characteristics of adopters and non-adopters (Mukherjee, 2020; Mukherjee et al., 2020; Mukherjee and Ryan, 2020). We investigated this further here using the 2016 Pobal HP Deprivation Index as a measure of regional socio-economic differences. Uptake is indeed correlated with lower levels of deprivation, having the biggest concentrations in the most urban (populous and resourceful) counties – Dublin, Cork, Galway, Wicklow, Meath, and Kildare. For context, at €24,969, the average disposable income in Dublin County in 2018 was 17.4% higher than the state average of €21,270, constituting the highest average disposable income per person in Ireland (Pobal HP Description 2016: marginally above average at 4.12) (CSO, 2018).

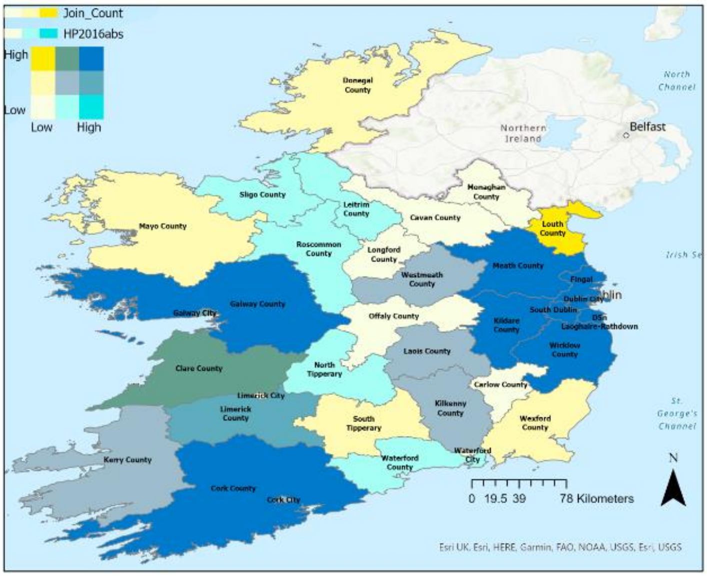


Figure 12 Bivariate plot of BEV adopter counts and the 2016 Pobal Deprivation Index by county, Pobal Maps, CSO. *Source: SEAI*

Figure 12 illustrates this wealth-adoption relationship using a bivariate plot of adopter count vs. deprivation index by county. Counties Cork and Galway are also marginally above average at 2016 index levels of 2.52 and 1.81, respectively. Counties Wicklow, Kildare and Meath house the key commuter towns for Dublin (and are typically also wealthier than the average county with 2016 index levels of 1.43, 3.42, and 1.83 respectively), and host above-average adopter numbers as well. County Louth (Pobal HP Description 2016: marginally below average at -2.96) is an interesting case, showing high levels of uptake paired with a low deprivation score.

This may be explained by the fact that Louth is the most densely populated county in Ireland outside Dublin, with a population density of 160 people per km^2, almost double the national average, housing a proportionate number of private car owners as well. Due to its close proximity to Dublin, County Louth is also home to two major commuter towns to Dublin, namely, Drogheda and Dundalk. The relatively short commutes between these towns and Dublin may mean that EVs are particularly suited to this population. County Louth also has one of the highest rates of unemployment in the country (CSO, 2017a). Hence, high BEV ownership despite higher levels of deprivation could also be partly explained by higher levels of income inequality. A considerable section of the population could be affluent enough to be able to afford EVs although a gap between the highest and lowest earners may bring the average disposable income for the region down.

We note that currently the used BEV market in Ireland is miniscule. In contrast, the average age of a vehicle in the Irish fleet (for all vehicle types) is 8.60 years and the average number of owners over the lifetime of the vehicle is 2.54 owners per vehicle, i.e., the majority of vehicles in Ireland are on their first, second or third owners (Cartell, 2020). This implies that a significant second-hand market exists for other vehicle types. When the supply of used BEVs increases, Figure 12 could look very different as new car buyers tend to be more affluent anyway and this effect could be partially interpretated as applicable to new vs. used car buyers rather than a BEV-specific effect. We tested this hypothesis using data from the CSO by running a simple linear regression of all new private vehicle registrations between 2013 and 2020 normalised by population on the Pobal HP Deprivation Index 2016 for each county. The results demonstrated no conclusive relationship between the two variables, implying that the positive correspondence between new BEV registrations and regional wealth goes beyond what we would expect to see for any new vehicle.

Figure 13 explores whether socio-economic disparities are reflected in BEV uptake within County Dublin as well given its prominence as an adopter hub. Indeed, EDs with above average wealth experience greater BEV uptake, such as Malahide (Pobal HP Deprivation Index: 8.45) and Dublin Airport (Pobal HP Deprivation Index: 7.2) in the North and Dún Laoghaire (Pobal HP Deprivation Index: 2.71) and Glencullen (Pobal HP Deprivation Index: 9.2) in the South.

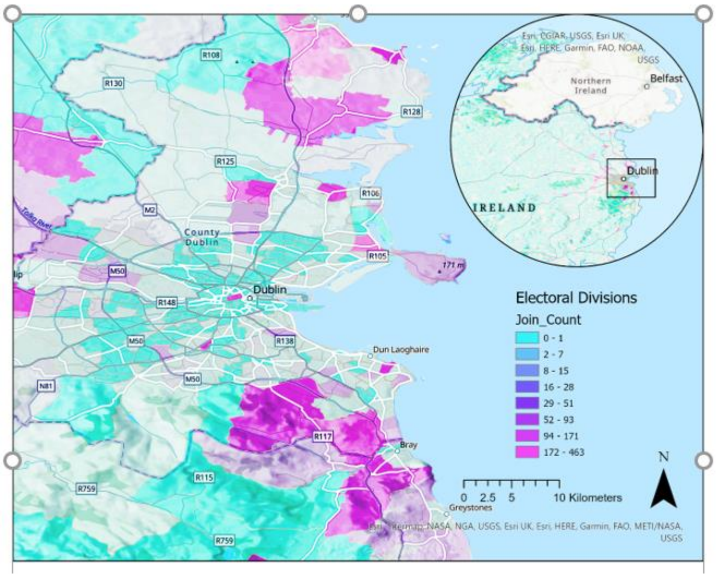


Figure 13 Socio-economic disparities correlate inversely with uptake in Dublin County, Pobal Maps, CSO. [Contrast pink with green areas for high vs. low adopter counts] *Source: SEAI*

A dimension of wealth that affects BEV uptake that the Pobal HP deprivation index does not cover is property ownership (Brückmann et al., 2021). Approximately 68% of Irish BEV adopters are homeowners. This fits with the current demographic of BEV owners (i.e., a mostly middle aged, high income, educated population) and is partly due to the traditional predominance of home ownership vs. renting in Irish culture. However, this trend is changing for the younger generation (people under 40), who, having faced multiple recessions in recent years, and possessing relatively lower disposable incomes paired with overinflated house prices and fewer or harder to attain financial supports, are finding it more and more difficult to own property (Horgan-Jones, 2019). Figure 14 illustrates relative property ownership shares of BEV adopters across all counties. The outsized role of home ownership in historical BEV uptake is very evident.

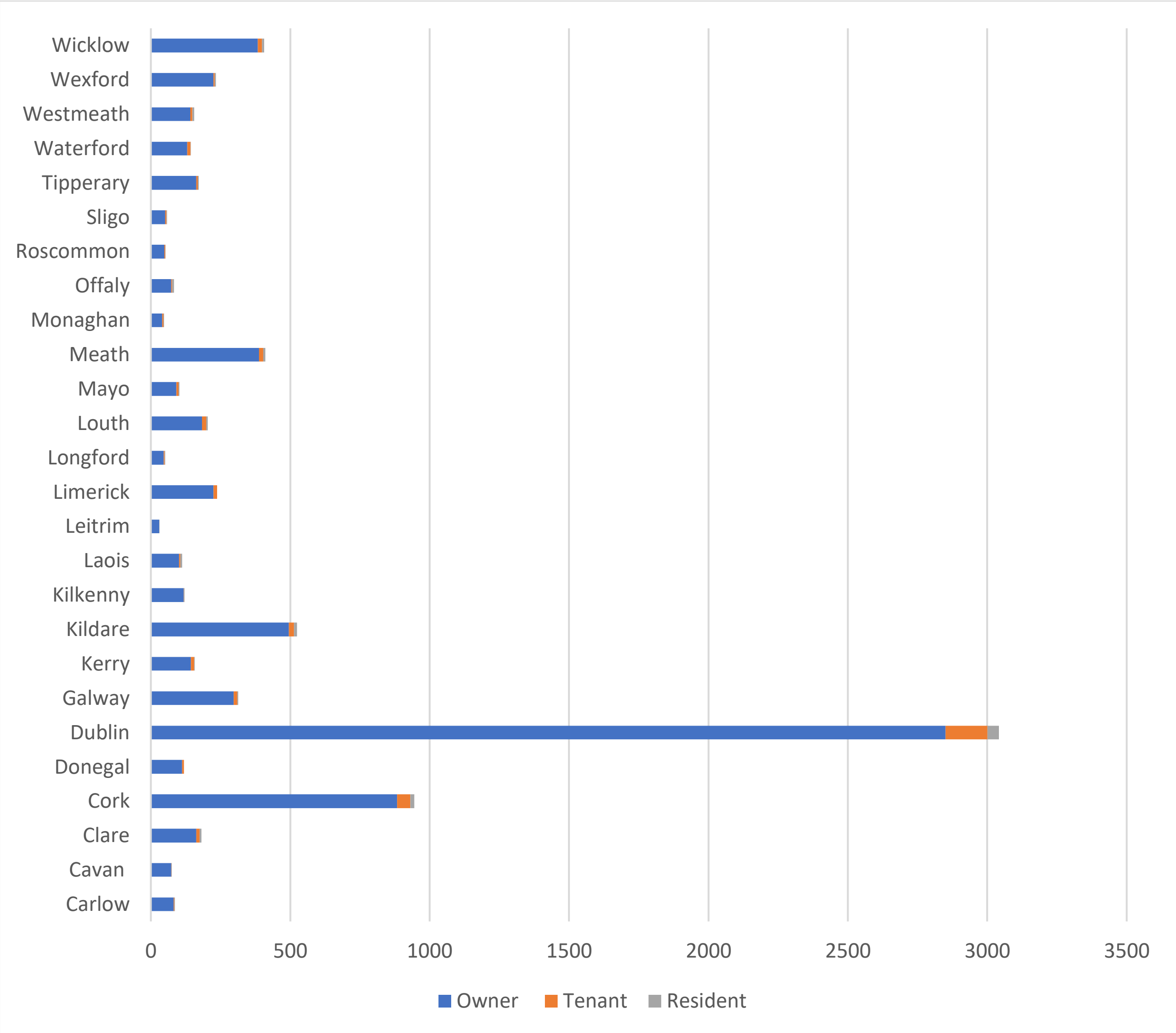


Figure 14 Property ownership status of BEV adopters by county as of November 2020. *Source: CSO*

Public charge point infrastructure and BEV adoption

Previous research identified a somewhat counter-intuitive negligible relationship between the existence of a public charging network and BEV uptake (Mukherjee and Ryan, 2020). The effect was in fact slightly positive, meaning that the further away someone was to a public charge point, the higher their likelihood of take-up was. Other studies support this weak relationship between out-of-home EV charger availability and BEV adoption probabilities as almost all charging events occur at home or at work for a majority of EV owners (Hardman et al., 2018). This paper explores charge points from a different perspective – that of the long-distance driver rather than the homeowner. Most Irish BEV drivers are homeowners with a home charge point and would therefore understandably value the existence of public charge points at strategic locations *en route* to their final destination, rather than necessarily benefiting from a public charge point at their doorstep as they generally prefer the convenience and certainty afforded by home charging.

Average commuting distances in Ireland are short compared to other European countries, with little distinction between urban and rural locations (CSO, 2017b). The average Irish commute is under 15km, with Dublin City, Cork City, and Galway City commuters living within 10km of their workplaces. Residents in Laois, a more rural setting, experience the longest commuting distances, at just over 25km. Thus, although the current range of BEVs should pose no problem for undertaking a journey this size, range anxiety is a possibility in psychological or rhetorical rather than technical or practical terms (Noel et al., 2019; Rauh et al., 2015; Viola, 2021; Yuan et al., 2018).[12] We investigated whether the coverage of public charging infrastructure really posed a practical problem for Irish BEV owners.

[12] The most popular BEV in Ireland in 2021 is the Volkswagen ID.3 which has an average range of up to 330km on a full charge.

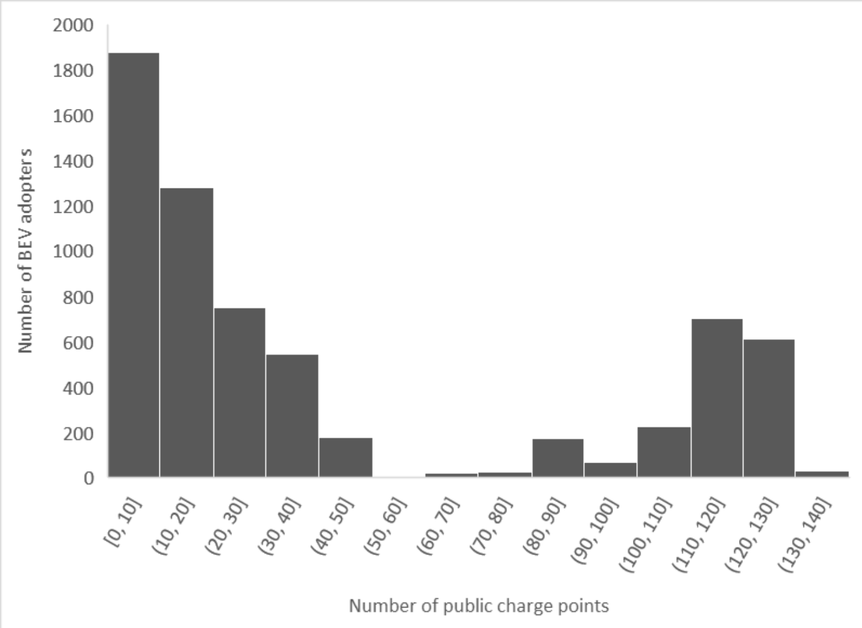


Figure 15 Frequency plot of public charge points within a 20km radius of each adopter.
Source: ESBN

The average journey distance in Ireland in 2019 was 13.7 kilometres (CSO, 2021b). Assuming a more generous commute distance of 20km, we estimated the number of public charge points installed within a 20km radius of each BEV adopter (Figure 15). The vast majority of adopters (n=1804) have between 1 and 10 chargers within this radius, with a small number (n=30) having access to over 130 chargers, implying that the availability of public chargers is generally not an issue. However, a small minority, 72 out of 6490 adopters, recorded access to zero public chargers, implying that there were still gaps in coverage.

We conducted a simple estimation of the location of blind spots in the Irish charging network coverage. Since we did not import actual street connection data, this is a rough estimation. First, we assumed an effective driving distance of a maximum of 200km/day (equivalent to the European average for short distance trips) and found no gaps in coverage (i.e., internal rings) (Eurostat, 2021). Of course, Ireland is much smaller than many European countries, so we assumed a more reasonable distance of 52km next.[13] An effective driving distance of 52km

[13] Note that this figure is for demonstration purposes only, as it is still likely higher than the distance most Irish drivers commute in a day and staying overnight in a location potentially provides access to a home charging point (CSO, 2021b, 2017b). Average European figures for daily commutes also tend to be under 50km. Interestingly, the all-electric range of PHEVs is typically 50km, around our assumed average daily mileage.

corresponds to a 20km buffer.[14] Considering a standard European street factor of 1.3, a driver whose BEV battery was low on charge could face issues if two of the charging stations on their way had a higher beeline distance than 52/1.3 ~ 40km.[15] That is, they could encounter issues if they were further than 20km away from one charging station and the distance to the next one was higher than 20km. The 20km buffer analysis identified eight internal rings along with a considerable lack of coverage along coastal County Galway and coastal County Mayo including the islands of Achill, Inisturk and Clare and the villages of Carrowteige, Carrownaglogh and Garterhill in Knockadaff, among others (Figure 16).[16,17] Table 1 lists the townlands located within the internal rings.

[14] A buffer is a reclassification of a point location based on distance. Buffering entails measuring distance outwards in all directions from an object to test a hypothesis based on proximity. If the buffer is uniform, as it is here, this distance is the same in all directions and is generally based on *a priori* knowledge (i.e., it is causative and measurable rather than arbitrary).

[15] The street factor accounts for the way European cities are planned, with streets running at right angles to each other forming a grid layout. Frequent intersections and an orthogonal geometry facilitate pedestrian movement and help with orientation. The typical street width, street length, block width and pavement width taken together mean that on average it practically requires ~1.3 times the straight-line distance between two locations to travel between them.

[16] For a 27km buffer, the number of internal rings was reduced to four with a section in the West coast also lacking coverage. Whilst two of these rings were irrelevant (one being under water and another an uninhabited area), the remaining comprised townlands in County Tipperary (Nickeres, Clashdrumsmith) and County Cork (Boherbue).

[17] Shorter effective driving distances would identify more internal rings (indicating greater lack of coverage) but this does not necessarily mean that a BEV driver making these journeys would exhaust all power, given the range of modern cars and assuming they had around 80% charge when they started out. Having access to more public chargers would serve the purpose of easing range anxiety in most cases, which is defined as worry on the part of the driver that their battery will run out of power before the destination or a suitable charging point is reached. Range anxiety is often cited as the most important reason why many are reluctant to buy BEVs.

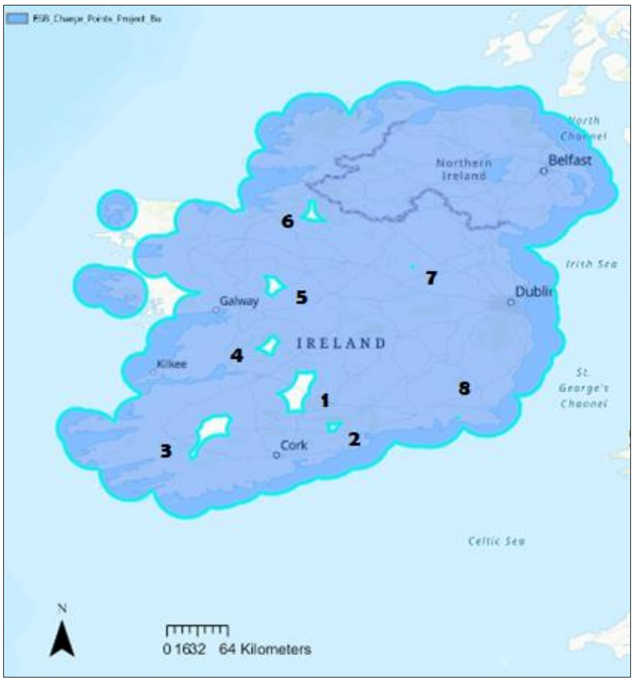


Figure 16 Buffer ring analysis of public charging network assuming an effective driving distance of 52km. *Source: ESBN*

We verified that these regions were inhabited (i.e., had no forest cover, boglands, lakes, or commercial agricultural areas). We found that they were rather small by comparing aerial maps with topographic maps sourced from the Environmental Protection Agency (EPA) Ireland and OSi's MapGenie web service accessed through the ArcGIS server (EPA Ireland, 2021; OSi, 2021b). Garryheakin in County Tipperary has, for instance, an area of 0.23 square miles, and is the 43,024th largest townland nationwide. Within County Tipperary, it is the 2,176th largest townland. Carrowteige in County Mayo has an area of 0.62 square miles and is the 16,332nd largest townland nationwide. Within Mayo, it is the 994th largest townland. For context, there are over 64,000 townlands in Ireland that can range from just a few acres in size to several hundred, particularly in mountainous regions.

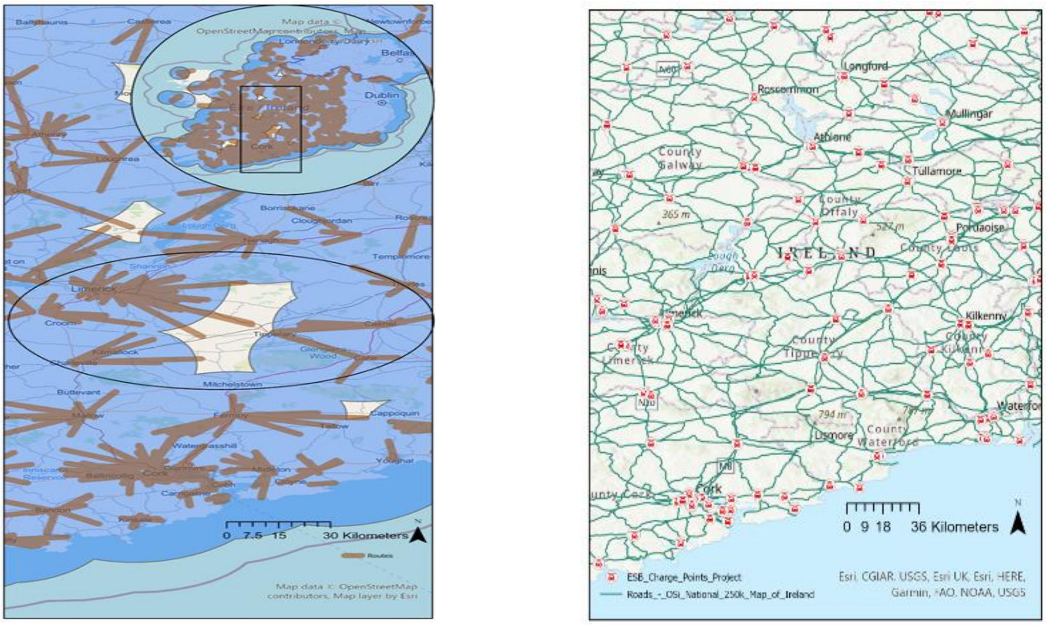
Table 1 Townlands contained within gaps in public charger coverage assuming an effective driving distance of 52km

Ring 1	Garryheakin, Emly, Doon, Cappagh, Hollyford village, Ballylanders (County Tipperary)
Ring 2	Lismore, Glenshask Beg, Moneygorm South (County Waterford)

Ring 3	Rathcoole, Dernagree, Newmarket, Lismire, Taur, Kishkeam Lower, Knocknagree, Rathmore, Boherbue (County Cork)
Ring 4	Bohatch North, Meenross, Raheen, Caherhurly, Tuamgraney, Scarriff, Capparoe, Aughrim, Poolnagour, Kildavin (County Limerick)
Ring 5	Carrowntober, Glen, Derrynabrin, Gunnode, Boherbannagh, Newbridge, Windfield, Mountbellow, Carrownagappul, Rahins Baunoges, Corgerry Oughter, Moylough More, Shankill West (County Galway)
Ring 6	Letter, Drumkeeran, Drummanfaughnan, Derrynahinch, Liscuillew Upper (County Leitrim)
Ring 7	Balnavine (County Westmeath)
Ring 8	Barrystown (County Wexford)

Finally, we used closest facility network analysis to verify whether any adopters resided within these service gaps, and where their closest public charge point currently was. Our analysis (Figure 17(a)) revealed that the largest distances travelled were in County Tipperary (Ring 1), where BEV users were potentially travelling a distance of either 20km to Cahir (to the right) or 29km to Limerick (to the left) to charge their cars using a public charger. Note that this analysis uses only the state-owned public charging network due to limitations in data availability for other network providers. Private players such as EasyGo have, in addition, a number of their own chargers whose geolocations we were unable to access.[18] However, ESB is still the largest national provider of e-chargers and the earliest, having entered the market in 2010/11 when the first EVs were introduced to Irish drivers.

[18] EasyGo is Ireland's largest eMobility Services Provider and its first private charging company hosting 400+ of their own chargers, 800+ ESB chargers and 20+ Circle K chargers on their network and has over 7,000 subscribers (EasyGo, 2021). Other small private players include Tesla, AppleGreen and Ionity that operate independently of ESB and EasyGo (Checkout, 2019; Ionity, 2021; Tesla, 2021).



(a) (b)

Figure 17 Closest facility network analysis: (a) lines connect each BEV adopter to their closest public charging facility. *Source: ESBN* (b) potential siting of public chargers along national road network. *Source: EPA*

Where more public charge points are desired, consumer behaviour and the current level of incentives are driving a move towards more charging stations rather than individual public charge points.[19] Studies have shown that the desired distances between charging stations correspond to the distances between existing gas stations with the mean preferred distance between two neighbouring charging stations being 7 km, whilst urban drivers prefer shorter distances than rural drivers (Pevec et al., 2020). Service stations alongside the national road network provide the most logical sites for new charging stations, as EV owners tend to

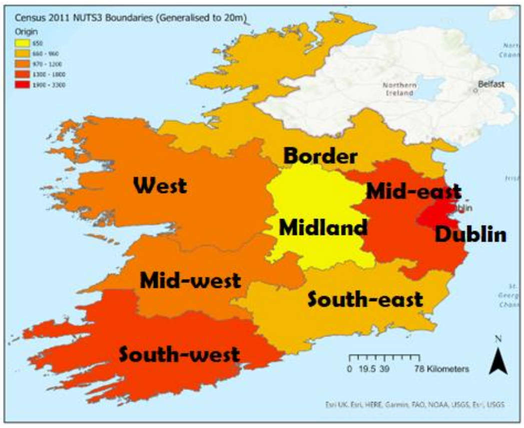
[19] A charging station is a collection of two or more individual charging points. Multiple charge points allow for simultaneous charging of two or more vehicles thus eliminating long waiting times and queues for users. Furthermore, businesses may gain higher returns on their investment from charging stations depending on the type of charger installed as well as energy resilience in emergency scenarios when they invest in chargers that are bi-directional, i.e., those that can convert and direct energy both into the car and out of it back to its source, using EVs plugged into the charging infrastructure as an energy source via their battery storage during power cuts or shortages. Government supports also tend to incentivise multiple charge point installations for businesses such as the UK Workplace Charging Scheme that allows the installation of up to 40 charge points and offers a generous grant of £14,000 per business to do so (UK Government, 2020).

primarily need to use public charging points on longer journeys. The primary and secondary road network in Ireland is ~5,306km long and is made up of motorways, dual carriageways and single lane roads (TII, 2021). Figure 17(b) presents a bird's eye view of the major road network (with red markers corresponding to current public charging infrastructure) in the area illustrated in Figure 17(a) (OSi, 2016). The road network provides information on potential siting venues for new public chargers, as workplaces tend to be concentrated close to motorways and alongside the existing public transit network.

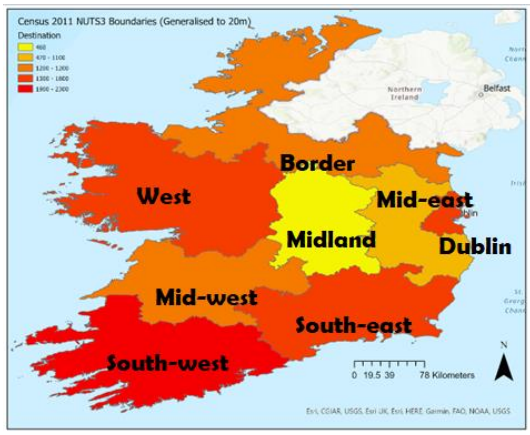
Although office car parks are often identified as a preferred location for public chargers, locating chargers in busy motorway junctions, for instance, could benefit a greater number of users commuting to and from work by providing both charging services as well as visibility, and thereby improving resource use efficiency. Motorway junctions are also particularly suitable for fast chargers and 24-hour charging stations that are free from usage restrictions such as allowing only a set period of time for charging or requiring an in-store purchase to recharge as may be the case for many charge points located in supermarkets, shopping centres, public car parks, and hotels. There is some recognition of this fact already as evidenced by the opening of the first eight-bay high-power charging hub (providing 150kW of power each) beside Junction 14 on the M7 motorway at Mayfield service station near Monasterevin, County Kildare, in July 2021 (IT, 2021).[20] This setup can deliver enough power in six minutes to drive a BEV for 100km. The project is part of a €20m investment programme financed by the government's climate action fund and ESB and there are plans to roll out 50 similar facilities across the country whilst simultaneously upgrading the national infrastructure (Hilliard, 2019)

Figure 18 compares the number of trips made by Irish residents (in thousands) in 2019 by origin and destination and shows that counties Dublin and Cork had a large population travelling outwards to other counties, particularly to the West and South-West of Ireland, underlining the importance of getting public charging facilities right in these particular regions. These long-distance drivers have much to gain from BEVs as the cost benefits increase considerably with distance travelled due to the lower running and maintenance costs of BEVs (Hagman et al., 2016). This is an opportunity that policymakers can harness when planning for new charging stations.

[20] Compared to this figure, standard home chargers only deliver between 3 and 6kW of power.



(a) Origin



(b) Destination

Figure 18 Choropleth maps showing the number of trips (thousands) by Origin and Destination by NUTS3 regions in Ireland in 2019. *Source: CSO*

Whilst the median BEV to public charge point ratio rose from 1.6 to 7.2 between 2015 and 2020 in Europe, Ireland had about 1,200+ chargers for an estimated 15,000 BEVs in February 2021, achieving a ratio of ~12.5 (Falchetta and Noussan, 2021). This is discouraging for Ireland’s immediate BEV uptake plans as it is quite high compared to the 2020 EU average of 9 for BEVs and PHEVs combined and compares poorly with the EU AFID’s recommendation of at most 10 passenger EVs per public recharging point (EU EAFO, 2021; European Court of Auditors, 2021). Moreover, the current network does not work seamlessly across the country as outages and system failure are frequently reported on public forums (IEVOA, 2021b). Additionally, more widespread use of EVs may lead to occasions (such as on national holidays) when pressure on public chargers may rise unexpectedly resulting in queues in key locations. Furthermore, the number of public charging facilities may not currently mirror regional population densities accurately. Assuming that the desirable number of charge points increases proportionately with population and county size, Table 2 compares a minimum number of charge points required to meet the needs of the population for each county (Ideal) against current provisions (Actual). Based on a simple spreadsheet model, there appears to be a few discrepancies between these figures.

Specifically, Galway, Mayo, Donegal, Kerry, Tipperary, Offaly, Cavan, Sligo, and Leitrim may benefit from new public charge point installations. In contrast, Limerick, Roscommon, Meath, Kilkenny, Westmeath, Kildare, Monaghan, and Longford appear to have met a minimum target, whilst Cork, Clare, Wexford, Wicklow, Waterford, Laois, Dublin, Carlow, and Louth appear to have a surplus of public chargers. This analysis does not however account for the economic standing of each region which in turn may influence travel behaviour and alter the dynamics of charging behaviour and thereby justify planning for different numbers of users and spatial coverage per charging point than this discussion allows. Dublin county has for instance ~16% of all chargers on the island of Ireland (and ~22% in the Republic of Ireland) but houses ~20% of the island's population, ~25% of Irish car drivers, and ~36% of BEV users, and is witness to some of the highest proportions of consumer spending on items ranging from housing to holidays, signifying greater disposable incomes and wealth than any other county (CSO, 2017c)**.** This implies that, although a minimum target has been met, more chargers may need to be prioritised here to support the higher number of BEV drivers in this region which is directly related to the region's economic activities.[21] In addition, Dublin city and suburbia enjoy heavy commuter traffic travelling in for business and commerce, which is all the more reason to maintain a surplus of chargers to serve the commuter population. A more detailed analysis of the minimum number of charge points will follow in future work.

Table 2 Ideal vs. actual provisions of public charge points across counties in Ireland based on size and population figures from the 2016 Census

County	Area (km^2)	Population Density ($/km^2$)	Ideal (% of total)	Actual (% of total)
Cork	7,500	72.3	8.37	9.52
Galway	6,149	42.0	6.74	4.49
Mayo	5,586	23.3	6.12	3.23
Donegal	4,861	32.6	5.33	4.31
Kerry	4,807	30.7	5.27	3.59
Tipperary	4,305	37.2	4.72	3.41
Clare	3,450	34.4	3.78	4.13
Limerick	2,756	70.8	3.02	3.77
Roscommon	2,548	25.3	2.79	2.87
Wexford	2,367	63.2	2.59	3.77
Meath	2,342	83.2	3.01	3.41
Kilkenny	2,073	47.8	2.27	2.33
Wicklow	2,027	70.2	2.22	4.13
Offaly	2,001	38.9	2.19	1.44
Cavan	1,932	39.3	2.12	1.26
Waterford	1,857	62.7	2.04	3.23
Westmeath	1,840	48.2	2.02	2.69

[21] Each of the 32 counties would host 3.1% of all chargers if counties were of equal size and population densities. However, these vary considerably, e.g., although Dublin is the 3rd smallest county by size, it has the highest population density.

Sligo	1,838	35.5	2.01	1.44
Laois	1,720	49.3	1.89	2.33
Kildare	1,695	131.0	3.43	3.95
Leitrim	1,590	20.1	1.74	0.72
Monaghan	1,295	47.3	1.42	1.26
Longford	1,091	37.4	1.20	1.26
Dublin	922	1,459.2	20.74	22.26
Carlow	897	63.4	0.98	1.26
Louth	826	155.4	1.99	3.95
Total - Ireland	84,252	77.9	100	100

In summary, some new infrastructure will thus be needed at strategic and easily accessible locations nationwide, especially rapid and fast public chargers for long distance commuters, which will involve cautious land use and financial management. A total of 1,400 charging points are planned for in the coming years as part of the government's programme such that EV drivers would never have to drive more than 30km to travel to recharge their vehicles (IT, 2021). Ultrafast chargers of the future will reduce waiting times drastically but are associated with significant power demand that the current substation and cable infrastructure cannot yet handle, necessitating the integration of future BEV penetration policy and emission reduction requirements with the electricity transmission grid and peak demand management (Hall and Lutsey, 2020; Hõimoja et al., 2012).[22]

On the other hand, home charging allows for more controlled charging and demand side management to prevent local network overloads during peak charging times (Brazil and Hoog, 2014).[23] Vehicle-to-grid solutions are a demand response strategy wherein BEVs act as energy storage units and BEV batteries supply power back to the grid or alter their charging rates during low generation periods (Yong et al., 2015). Widespread adoption of rapid charging would reduce opportunities for this kind of system management. Where new public charge points are required, providers must be careful to maintain a balance of slow and fast chargers perhaps favouring a small number of redundant slow chargers in places of public interest over an excess of more expensive and power-hungry rapid and fast chargers, and instead installing

[22] A case in point is the new facility at Mayfield which has to be supported by a new substation nearby.

[23] An overuse of the high-speed public charging network could easily trip power generators if demand for charging concentrates around existing peaks in electricity demand such as 'rush' hour surges on the way to and from work, especially if power comes from intermittent sources such as wind or solar. Thus, more public chargers is not necessarily the answer to managing increasing demand.

more of the latter primarily to accommodate any additional unforeseen demand at least until the power infrastructure can be sufficiently upgraded to handle additional loads.

4. Conclusions and policy implications

We are undoubtedly on the cusp of a technological revolution across transport and energy, whereby electrification is set to become our future. We are also at a time when rising consumer awareness of environmental issues and knowledge and skills in predicting the financial benefits and costs of BEVs vs. ICEVs have had a steady influence in driving BEV sales upwards EU-wide in recent years. This paper explores Irish BEV sales trends in this context. It analyses BEV sales data between January 2015 and May 2021 and shows that the pattern of uptake has geographical significance, requiring that any policy measures to encourage further uptake be based on real world distributional implications. The overarching goal of this work is to develop methods and tools to support the development of data-driven interventions in future BEV policy.

The findings from this work estimate that Ireland may reach peak BEV sales of 32,513 BEVs between 2025 and 2030 given current trends, which is far below a market potential of 3 million vehicles that could potentially be achieved by 2040 assuming every ICEV is replaced by a BEV. Moreover, the Government of Ireland’s Climate Action Plan (CAP) in 2019 commits to a target of 936,000 EVs on Irish roads, including 840,000 passenger EVs, by 2030 (DCCAE, 2019). There will need to be 180,000 EVs on the road by 2025 to meet this target, which does not align with the results from our model based on historical data. CAP 2021 is likely to increase this target further, which implies that the updated BEV targets will only be achievable with additional government supports that change the current underlying trends (or parameters in the model). To reduce the perceived costs of switching to BEVs, BEVs must be presented as close substitutes to ICEVs. More BEV models must also reach cost parity with ICEVs and eventually become cheaper, such that no financial barriers remain. Meanwhile, policymakers can influence uptake now by artificially reducing the upfront costs of purchasing BEVs further, to mimic a situation where price parity has already been achieved for most models such that social contagion can kick in to encourage mainstream adoption (as has happened in Norway).[24] Simultaneously, studies have cautioned that a diversity of transportation modes will be needed in the future and alternative mobility solutions must be explored such as shared mobility options that not only reduce emissions more effectively but also free up space that can then be designated for green mobility, such as cycle tracks, bus lanes, and compact, walkable spaces (Henderson, 2020; Senecal and Leach, 2019).

PHEVs are a potential stopgap 'transition technology' between 100% fossil fuels and 100% electric and interestingly, PHEV adoption had increased rapidly in Ireland and contributed to ~6,000 EV sales at the start of 2021 due to the phasing out of subsidies that had influenced BEV uptake in the past (CSO, 2021a; O'Sullivan, 2021). It is likely that PHEV sales will keep growing in the foreseeable future and eventually overtake ICEV sales. However, PHEVs are now receiving fewer policy supports at the EU level given new evidence of the discrepancies between actual and claimed emission levels of the technology (Manthey, 2021). Although Irish regulation mandates that all new cars be either battery electric or plug-in hybrid by 2030, ensuring a larger BEV to PHEV share is essential in light of this evidence. Rapid advancements in battery technology has meant the advent of long range BEVs (>400km) which has made public charging infrastructure less relevant for many drivers. Thus, the continually improving battery range paired with greater ease of access to reliable charging infrastructure will be strong enablers in the transition from ICEVs to BEVs. Accordingly, it is prudent that a majority of the market potential of 3 million private vehicles up to 2040 be met with BEVs.

Overall, BEV adoption appears to be a geographically heterogeneous phenomenon, and thus, there should be a heterogeneous policy response to it. Lower adoption in rural areas could partly be attributed to sparse population. However, our insights point to a rural-urban divide beyond what is reasonably expected due to variations in population densities. This underscores the importance of considering regional differences in policy design, given that policies are generally implemented at the national level, and monitoring and evaluation processes may not typically account for distinctions in needs and priorities at sub-national levels.

[24] In 2020, Norway became the first country where EVs outsold ICEVs, with 54.3% of all new cars sold being pure electric. The Norwegian government has made this possible through generous tax breaks for zero-emission vehicles imposed as part of a goal to become the first European country to end the sales of ICEVs by 2025.

Our analysis also suggests that relative deprivation is inversely correlated with BEV uptake: varying levels of development mean that residential areas are spread out whilst workplaces are concentrated, with implications on the growing distance between work and home and thus how transport is used and its associated carbon emissions. Cities and towns tend to grow fastest at the edges, resulting in a static or declining population in town centres. Affordability and availability of housing and the quality of our environment also tend to be better in the peripheries. A case in point is Dublin. Economic activity has been shifting eastwards due to the development of Dublin in the last ~30 years, and the physical footprint of Dublin itself has grown rapidly to commuter catchments, which partly explains why Dublin and surrounding counties have experienced greater BEV uptake than the state average. However, an overemphasis on urban centres will preclude opportunities to expand uptake in rural areas, where people have the capacity for home charging and have otherwise little public transport alternatives to reduce their carbon footprint. Thus, policymakers must close any regional divides in access to information and resources that may hinder BEV take-up and instead promote BEVs as suitable alternatives to ICEVs in both rural and urban areas.

To this end, firstly, access to information must be prioritised through inclusive broadband coverage for every region as the adoption of new technologies, especially BEVs, involves a steep learning curve, and users tend to benefit more from access to information online than car dealerships as they currently operate (Jang et al., 2017; Mukherjee et al., 2020; Mukherjee and Ryan, 2020). This is because many car dealerships are still ill-equipped to answer customers' queries around EVs and reliable internet coverage becomes necessary for accessing available information regarding public charging infrastructure, for instance, as many individuals and companies active in this space currently operate online primarily through mobile applications (Krishna, 2021). The internet also provides greater convenience for the transmission of information in general. In 2020, 92% of households had access to the internet at home, with much of rural Ireland having limited access to high-speed broadband services (Statista Research Department, 2021). Fortunately, better internet access is currently being facilitated through the Government of Ireland's investment in a National Broadband Plan which focuses particularly on rural and remote areas in which commercial broadband providers do not currently operate (NBI, 2021).

Secondly, measures to encourage uptake in deprived areas could be considered such as differential subsidy levels or vehicle charging rates based on location. Furthermore, gaps in public charger coverage must be reduced further in townlands, and coastal and rural communities particularly in the West and South-West of Ireland to overcome range anxiety amongst potential adopters living and working in those regions and those commuting into them either for personal, leisure, business or commercial purposes (such as electrified road freight transport). A more extensive and reliable charging network would also need to be prioritised for those living in rental properties and apartment buildings especially in rural and suburban areas without adequate public charging facilities and in areas with high levels of transient populations such as Temple bar in Dublin city centre where there are fewer economic incentives to install home chargers due to the high resident turnover rate.

A high level of property rentals in Ireland is socio-economically problematic, and policy must address this pressing issue, but this also has implications for BEV ownership, as the economics of rental properties provides few incentives for landlords to install charge points at home (or undertake other major home renovations) and for tenants to pay for these out-of-pocket in exchange for uncertainties on rent costs and length of lease (Melvin, 2018). Government intervention in extending the public charging infrastructure is justified where there is a known market failure, in this instance, expanding charging infrastructure around rental properties may be necessary where renters may have a latent demand for BEVs but have no access to off-street parking or garage space for home charging. A general policy implication to enable home charging is that all households should continue to receive subsidised home charge points and new builds should have built-in charging infrastructure on site to facilitate overnight home charging especially in apartment blocks and communal establishments. Where multiple charge point providers are involved, an industry-wide agreement on connectors and payment will be crucial as the number of possible options for both is too varied and thereby too cumbersome at present.

Often, a sense of place is a psychological construct rather than a material reality, and perhaps *perceptions* of infrastructure coverage has triggered certain behavioural responses for long-distance commuters, the group most likely to still cite a lack of public infrastructure as a major barrier to uptake (AAA, 2019; Venson media, 2019; Viola, 2021). Measures such as clear signage and providing tailored compatibility information could help mitigate this issue (Herberz and Brosch, 2021). Whilst national policies often take years to change locked-in infrastructure and institutions, behavioural shifts have the potential to be more rapid and widespread; perceptions of a gap in infrastructure where it does not exist could also be mitigated through other behavioural interventions such as awareness raising, habit intervention, engaging selective attention, and improving education on the extent and use of current public charging infrastructure (Broadbent et al., 2021; DellaValle and Zubaryeva, 2019; Sustainable Energy Authority of Ireland, 2020). The development of charging infrastructure must go hand in hand with the creation of viable and flourishing second-hand markets for BEVs that also plan for their end of life, and shared mobility services especially in rural areas that have the potential to reduce the personal footprint of travel even further (Wappelhorst, 2021).

As a whole, whilst improved vehicular efficiency standards, cleaner fuels, and sustainable and compact cities that advance public transport, walking and cycling, and change how people and goods move, will all contribute to reducing transport emissions, a complete sustainable mode shift cannot be expected, and therefore transitioning to zero-emissions transport will be a crucial component of the solution mix (Carroll et al., 2021). Electrification eliminates tailpipe emissions of CO_2 and harmful particulate matter whilst simultaneously harnessing our incredible potential to decarbonise the power grid and contributing to grid resilience (Malmgren, 2016).

Irish EV uptake still lags behind its EU peers, however (Hall et al., 2020). Irish EV policy has historically been static with incentive structures that have delivered poor CO_2 reductions in proportion to policy costs, overemphasised fiscal instruments that were stacked against the poor, and lacked clarity over the future of diesel vehicles (O'Neill et al., 2019; O'Sullivan, 2021). In line with targets, the government's proposed EV policy must be implemented conscientiously at the earliest to have any measurable impacts on emissions levels in the decade ahead (Alam et al., 2017). The government's Project Ireland 2040 has been a positive move that seeks to redress issues with past policy that saw public investment spread too thinly and investment decisions misaligned with a well-defined strategy.[25] To strengthen this project's ambitions, we propose a more responsive transport policy approach that connects rural-urban communities better and addresses regional imbalance as a key step towards achieving Ireland's emissions goals and shared vision for a sustainable future, at least until BEV uptake reaches

[25] The National Development Plan (NDP) and the National Planning Framework (NPF) combine to form Project Ireland 2040. The NPF sets the vision and strategy for the development of Ireland to 2040 whilst the NDP provides enabling investment in physical infrastructure and business and community support to implement the strategy.

the tipping point. As awareness, acceptance, and model availability continue to grow and expand the BEV choice set for Irish customers, and prices simultaneously plummet, this provides an opportune moment to get the BEV policy right to encourage further uptake and help decarbonise the transport sector faster.[26]

A limitation of this study is that it is based on less than a decade of BEV diffusion data for Ireland, whilst to accurately systematise and quantify a pattern of growth and structural change requires sufficiently long historical data. Thus, without knowledge of the saturation level *a priori*, statistical uncertainty in the estimated parameters in the Bass diffusion model cannot be ruled out due to data limitations. Further analysis will investigate in more detail the minimum number of public charge points required to support the widespread use of BEVs, the current use of public space for charging, the location allocation problem of additional charge points where coverage is currently lacking and routing and service area analysis using road network data and real-time drive times. We will also explore travel and charging behaviour in terms of how people use public chargers in the real world as a better indicator of the role of charge points in BEV uptake.

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[26] There has been a huge growth in the number and types of EVs available to buy under the SEAI grant scheme, with almost 100 now eligible for grants.

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