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The cost of electrifying private transport – Evidence from an empirical consumer choice model of Ireland and Denmark

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ABSTRACT

There is a growing consensus that moving to a low carbon future within the transport sector will require a substantial shift away from fossil fuels toward more sustainable means of transport. A particular emphasis has been given to battery electric vehicles (BEV) and plug in hybrid electric vehicles (PHEV), with many nations investing in improving their charging infrastructure and incentivising electric vehicle purchasing through offering grant schemes and tax relief to consumers. Despite these incentives, the uptake of BEVs and PHEVs has been low, while some countries, such as Ireland and Denmark, are in the process of removing the tax relief currently in place. This initial retraction has already been met with a fall in sales of BEVs and PHEVs, which is expected to continue decreasing as these incentives are further reduced. This study develops a socio-economic consumer choice model of the private transport sector based off national empirical data for Ireland and Denmark to analyse the long-term effects of these subsidy retractions, and to further analyse the policy measures and associated cost of moving toward a low carbon private transport sector.

1. Introduction & motivation

There is a growing consensus that moving to a low carbon future within the transport sector will require a significant shift from its current state, whereby conventional fossil fuelled internal combustion engines (ICE) dominate the market, to sustainable means of transportation (IPCC, 2014). This shift is considerable, as it requires a fundamental change in both the fuel type and the vehicle technology of the transportation sector. Considering private transport, which constitutes 42% of global well-to-wheel (WTW) transport related emissions (IEA, 2017), this shift will involve multiple agents. *Fuel suppliers* may provide emission reductions through altering the composition of the fuels offered to consumers vis-à-vis the blending of bio-ethanol and bio-diesel with gasoline and diesel respectively or providing new fuels (e.g. CNG, LPG or H_2). *Automobile manufacturers* may provide efficiency improvements and innovative technologies capable of reducing downstream vehicle emissions. *Governing bodies* may impose regulations through fuel standards and minimal requirements for the performance of new vehicles while also incentivising the sale of low emitting vehicles. Finally, *consumers* – arguably the most vital agent in private transportation – choose which vehicle technology to purchase.

The potential emission reductions available from these former two supply agents are constrained by current technological

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limitations. European fuel standards, for example, mandate a maximum blend of conventional biofuel with petrol and diesel ICEs at 5% (CEN, 2008) and 7% (CEN, 2009) respectively, while the long-term efficiency improvement potential available to conventional ICEs has been identified as 28% and 33% for a spark ignition and compression ignition engine respectively, relative to a 2005 spark ignition engine (IEA, 2008).[1] While these measures offer potential short-term and medium-term solutions to meeting national emissions reduction targets, increasing the penetration of low-carbon alternative fuelled vehicles (AFV) will be imperative in advancing toward carbon reductions capable of adhering to a future with a global temperature rise limited to less than 2 °C (IEA, 2017). Despite this necessity, the uptake of non-ICE vehicles has been very low, suggesting that numerous barriers prevent a significant deployment of these vehicles. Moreover, the price of removing these barriers can be rather costly in the short-term, with little certainty surrounding effectiveness.

To quantify these barriers, the many costs pertaining to vehicle consumer choice can be loosely grouped as *tangible costs* and *intangible costs*. *Tangible costs* consist of the actual costs the consumer is faced with when choosing a vehicle, e.g., investment cost, operational and maintenance costs (O&M), taxation, and fuel costs. The nature of these costs allows for a quantifiable monetary figure to be associated with each factor. *Intangible costs*, however, represent the many non-monetary perceived costs the consumer faces when using a vehicle, e.g., inconvenience due to low vehicle range and limited refuelling infrastructure, to acceptance of new and uncertain technologies and to fewer options about the characteristics of the vehicle, e.g., number of doors, colours available, size, etc. These costs are generally difficult to quantify, as their perception changes for different consumer groups. Nonetheless, for regulators it is important to account for these intangible costs in their planning as to elaborate effective strategies to remove these barriers.

This study presents a methodology which monetises these intangible costs using empirical data from national sources to create a dynamic consumer choice model of the private car sector for Ireland and Denmark. This consumer choice model is linked to a sectoral simulation model of the private car sector (the CarSTOCK model) to indicate the cost and potential effectiveness of policy interventions in the form of WTW carbon dioxide (CO_2) emission savings. Ireland and Denmark have been chosen as a case study as both are in the process of removing subsidies for battery electric vehicles (BEV) and plug in hybrid electric vehicles (PHEV) by the turn of the decade (see Fig. 1 for a detailed breakdown) (Department of Finance, 2017; Skatteministeriet, 2015). In the case of Denmark, the initial retraction of the VRT subsidy for BEVs and PHEVs in 2016 was met with a drop in combined BEV and PHEV sales of 42% relative to the previous year (EEA, 2017). These subsidy withdrawals have been announced despite both countries identifying the necessity of electrifying transport in moving toward a low carbon future (DECLG, 2016; The Ministry of Climate Energy and Building, 2013).

The purpose of this study is threefold; (i) to contribute to the current body of scientific literature surrounding the area of modelling consumer choice within the private transport sector through use of qualitative data, (ii) to determine the effect of revoking tax relief for BEVs and PHEVs in Ireland and Denmark on stock and emissions, and (iii) to determine the cost and effectiveness of implementing further governmental level policy measures incentivising BEV and PHEV purchasing, In keeping with the order of these points of purpose, this paper is structured similarly. Section 2 discusses the value of modelling consumer choice within the transport sector, Section 3 describes the model inputs, structure and operability, Section 4 presents the impact of varying the market determinants mentioned above and Section 5 concludes.

2. The importance of modelling consumer choice

There is a growing body of literature which emphasises the necessity of moving away from models driven solely by economic parameters by including attributes related to consumer behaviour, thus enabling a more accurate representation of consumer choice (Byun et al., 2018; Garcia-Sierra et al., 2015; He et al., 2012; Mabit, 2014; Tattini et al., 2018; Zhang et al., 2016). This is imperative when analysing how to facilitate the shift toward sustainable mobility: without differentiating heterogeneous consumer groups and capturing the barriers that oppose the uptake of alternative fuelled vehicles (AFV) for these groups, both governing bodies and modellers alike are liable to an over-simplified representation of the market which they are attempting to alter. This over-simplified representation in turn may lead to unrealistic scenarios for the modeller and ineffective policies for the policy maker.

In an ideal consumer choice model, each agent would have a singular representation, with every applicable behavioural attribute accounted for to determine the utility of each vehicle available to purchase. In this way, the least-cost process of improving AFV utility for each consumer could be tackled. Of course, the scope of such an ideal representation would not only require a substantial level of computing power to model, but also an extensive data set to drive achievable, possibly through a comprehensive stated preference survey (SPS). There is a certain need for consumer specific data to accurately model vehicle consumer choice (Daziano and Chiew, 2012), although the availability of data is constrained. Thus, while aiming at developing a representative and valid model, we need to limit both the number of consumer segments and applicable behaviour attributes.

2.1. Consumer segments

Behaviour economics and psychology play a central role in breaking down the complex nature of the rationale behind consumer behaviour into comprehensible segments (Mattauch et al., 2016). These segments can be defined by many different attributes, e.g., demography, geography, and driving profiles. While consumers can be defined by a wide ranging array of these segments branches, it

[1] These efficiency improvements are gained through a combination of reducing engine friction, starter-alternator components, variable valve lift and timing, advanced cooling circuits, electric water pumps, and transmission improvements.

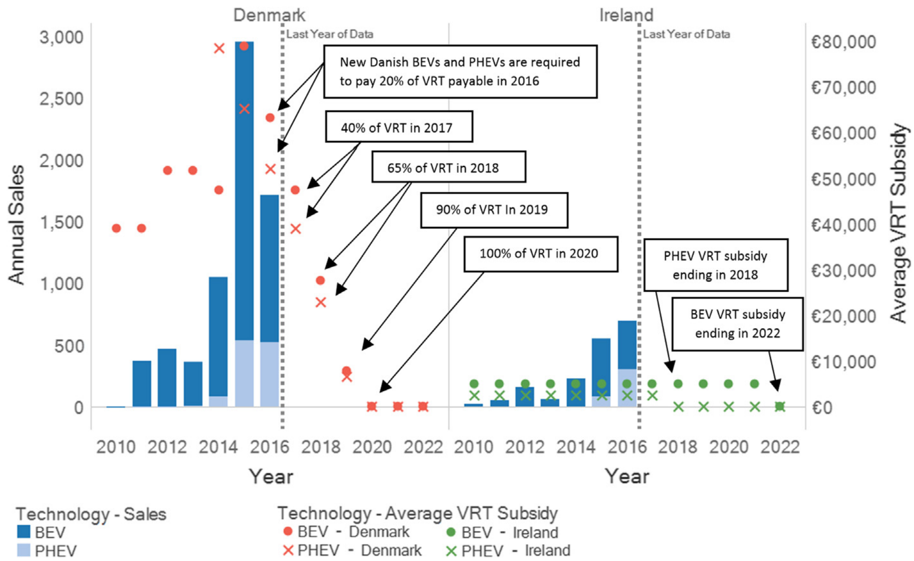

Fig. 1. Sales of BEVs and PHEVs in Denmark and Ireland (bars) and corresponding average VRT relief (the Danish VRT system is based on the cost of the vehicle (105% of the first 81,700 DKK (€10,800) and 180% of the remainder) with further slight subsidies for all vehicles dependant on fuel efficiency. The VRT relief for BEVs and PHEVs was calculated from the annual sales weighted average cost of the vehicle, while the projected VRT relief was calculated by holding the vehicle cost constant from 2015 onward and decreasing the VRT relief according to the text in Fig. 1) available (shapes).

is necessary to identify those which can be accurately represented (for the modeller) and those which can act as a policy lever (for the policy maker). Numerous studies have been dedicated to identifying these important behaviour attributes influencing consumer choice of private vehicles. For example, (Wilson et al., 2014) created a synthesis of 16 peer-reviewed articles which use discrete choice experiments informed by SPSs in examining preferences for AFVs. The studies analysed had a wide geographical range with findings that socio-demographic characteristics - particularly age, gender, and education - influence choices. Social influences were found to be important, although are rarely modelled. These characteristics can be used to segment consumers in adopter categories. Roger's classification of technology adopter types is a common framework for segmenting consumers, whereby the market is split into different classes of innovators (Rogers Everett, 1995). Combining the results of SPSs with Roger's diffusion of innovation theory provides a means of differentiating the innovators of a market, who would be the likely early investors in AFVs, from the laggards, who would be more reluctant from investing in new technologies. Creating these segments allows the modeller to vary behaviour attributes, e.g., range anxiety, for different portions of the market and for the policy maker to target consumer groups more effectively. Further examples of transport discrete choice models which segment the market by varying levels of innovations can be found in Brand et al. (2017), McCollum et al. (2016), and Bunch et al. (2015).

2.2. Behaviour attributes

As with consumer segments, the number of behaviour attributes which affect private vehicle-related purchasing decisions are wide ranging and are commonly left unrepresented in traditional energy system models. For energy systems models that wish to include heterogeneous decision agents, it is extremely difficult to represent all relevant behaviour attributes related to vehicle purchasing (McCollum et al., 2016), forcing these models to limit the inclusion of these attributes to those relevant for a specific research question.

This study draws upon the findings from the MA^{3}T model, a nested multinomial logit (MNL) choice model developed by Oak Ridge National Laboratory, which uses the US National Household Travel Survey to determine the disutility costs (the non-monetary adverse effects faced by the consumer when purchasing a vehicle) associated with many of these attributes. Studies from this model determined vehicle model availability, risk related disutility, range anxiety, and refuelling/recharging infrastructure availability to be amongst the greatest contributors (Lin and Greene, 2011). This is broadly in agreement with the findings of both Wilson et al. (2014) and Sierzchula et al. (2014), and thus stands as the extent of behaviour attributes examined within this study.

2.2.1. Model availability and risk related disutility

There are a wide range of vehicle characteristics which may influence a consumer's preference when purchasing a vehicle, e.g., car brand/model, vehicle cabin (sedan, hatch back, station wagon), engine type, car weight, car power, transmission system, number of doors, colour, alloy frame, etc. Although each of these characteristics can be individually classified as a behaviour attribute, they may be grouped under the overarching theme of model availability. Automobile manufacturers, in general, aim to provide a wide array of vehicles which fulfil the individual preferences of as many consumer segments as possible. Thus, the magnitude of the disutility cost associated with model availability for a vehicle class rises as the number of models available fall, and vice versa.

Prior to achieving a substantial market share, new technologies are generally met with a varying level of aversion toward adoption, dependent on the consumer segment. The early adopters, in accordance with the theory pertaining to the diffusion of innovations, perceive this risk to be negative as the novelty of a new technology is appealing to this consumer group. On the other hand, their laggards' counterpart perceive it to be positive due to unfamiliarity. The disutility cost associated to this attribute is only relevant to AFVs as conventional ICEs are now widely accepted across all consumer segments. As the adoption of a particular AFV becomes widespread in a certain market, the risk related disutility converges on zero.

2.2.2. Range anxiety and refuelling infrastructure

There is a disutility cost associated with both range anxiety - a term used to encompass the perceived penalty associated with a failure to meet a daily travel demand due to limited battery range – and limited availability of refuelling infrastructure. Both of these disutility costs vary dependant on the travel profile of a consumer, while the magnitude of these costs varies based on the efficiency and range of a vehicle, alongside the recharging/refuelling infrastructure availability for the fuel used. Range anxiety has an associated penalty perceived by the consumer, which varies over time as a technology becomes more widespread. The disutility cost of range anxiety is faced only by BEVs, as the consumer acceptance of ICEs and PHEVs prevents any associated risk with this attribute. Refuelling infrastructure represents a disutility faced by all vehicle types, although the strong presence of petrol and diesel refuelling stations globally renders this cost to be minimal for ICEs.

3. Methodological approach

The approach employed by this study develops a non-linear consumer choice model of the private transport sector for Denmark and Ireland and links the outputs of this model to a sectoral simulation model of the private car sector to generate the resulting change stock and WTW CO_2 emissions due to governmental policies. Both models use the base year of 2015. This work has been largely inspired by previous discrete consumer choice models (Bunch et al., 2015; McCollum et al., 2016), and expands on these pieces of work through the integration of a sectoral simulation model and the reliance on publicly available data related to the private vehicle market.

The consumer choice model embodies the tangible costs faced by the consumer along with a monetised representation of the intangible costs related to model availability, risk related disutility, range anxiety, and refuelling infrastructure. These intangible costs are monetised via publicly available empirical data, where possible, to provide a method which is replicable for other countries with similar data availability. This study differs from most consumer choice models to date by relying on revealed preference of consumers shown through publicly available empirical data rather than stated preference, as was the case in Bunch et al. (2015) and Hackbarth and Madlener (2013).

This consumer choice model computes only the private vehicle market shares, and cannot determine the impact of policy measures on aggregate stock or emissions. To account for this, the CarSTOCK model is linked with the consumer choicemodel. The CarSTOCK model is a bottom-up techno-economic model which uses the market shares from the socio-economic consumer choicemodel, in tandem with a technically detailed representation of the transport sector, to provide a full representative of the breakdown of stock, energy consumption, activity, and WTW CO_2 emissions in both Ireland and Denmark, thus determining the net effect of policy measures.

Scenario development is finally carried out within the consumer choicemodel, whereby policy specific scenarios pertaining to changes in vehicle registration tax (VRT), value added tax (VAT), annual motor tax (AMT), market regulation, and fuel costs, are created, resulting in detailed market shares of each 15 private vehicle technologies explored. These market shares are then entered into the CarSTOCK models for Ireland and Denmark to simulate the effect these policy measures would have on long-term stock, WTW CO_2 emissions, and energy consumption. This full method is summarised in Fig. 2.

3.1. Consumer choice model

The consumer choice model used in this study is a non-linear socio-economic Excel-based model built to estimate the effect of various policy measures on the private vehicle market. The market share (MS) for each vehicle is calculated based off the comparative perceived life cycle costs (LCC) of each vehicle technology using Eqs. (1) and (2), which are derived from the CIMS-US hybrid energy-economy model (Jaccard, 2009).

$$MS_{j,s} = \frac{(LCC_{j,s})^{-v_a}}{\sum_{k=1}^{K}(LCC_{k,s})^{-v_a}} \tag{1}$$

$$LCC_{j,s} = \left(CC_{j,s} * \frac{r}{1+(1+r)^{-n}} + MC_{j,s} + FC_{j,s} + IC_{j,s}\right) \tag{2}$$

In this approach, market share (MS) is calculated for each technology (j) and segment (s) in year n accounting for tangible costs - capital costs (CC) (which includes purchasing related taxes), maintenance costs (MC), and fuel costs (FC) - and intangible costs (IC) - which is a combination of costs associated with the behaviour attributes defined in Section 2.2. Capital costs are annualised, in order to be made comparable with all other costs, through the use of a discount factor r with a value of 25.7%, which is the current discount

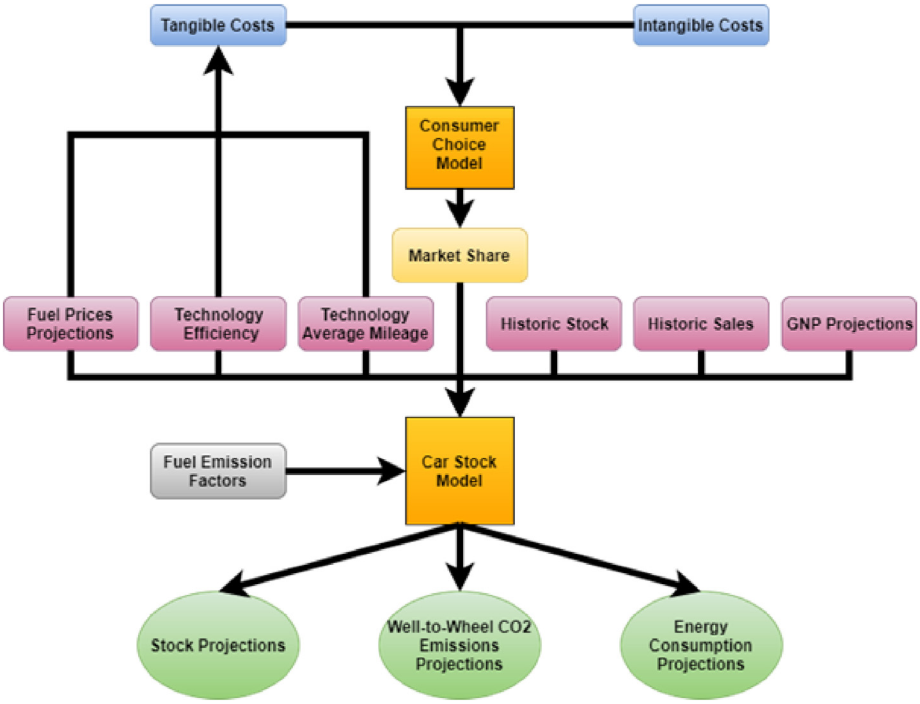

Fig. 2. Multi-model methodology.

rate for private cars adopted in the full CIMS-US model. This value was chosen for a discount factor as the methodology adopted by this study expands upon the original CIMS-US methodology, and so assumptions were aligned where possible. This falls within the range of vehicle related discount factors used from the review of similar values within literature carried out by Train (1985). A variance parameter (v_a) is introduced to enable a more behaviourally realistic allotment of market shares to the vehicle technologies. A high value of v represents a 'winner takes all' phenomenon whereby the lowest costing vehicle takes close to all of vehicle sales within a segment. On the contrary, a low value of v distributes sales more evenly regardless of differences in life-cycle costs, where a value of 0 produces a completely even share across all technologies. The variance parameter, v_a, was carried over from the CIMS-US model which uses a value of 15 (see Rivers and Jaccard (2005) for more details on the calculation of v_a). A sensitivity of the results through varying the variance parameter can be found in Appendix A. This study takes the approach adopted in CIMS-US further through consumer segmentation and substitution of the intangible costs with functions based on the model availability and range anxiety.

In both Ireland and Denmark this market is heterogeneous, so the segmentation of the market is critical to appropriate the variance in intangible costs accurately. Based on the review carried out in Section 2.1, the private vehicle consumer market is split into 18 segments divided geographically (urban/rural), by driving profile (Modest Driver, Average Driver, Frequent Driver) and by

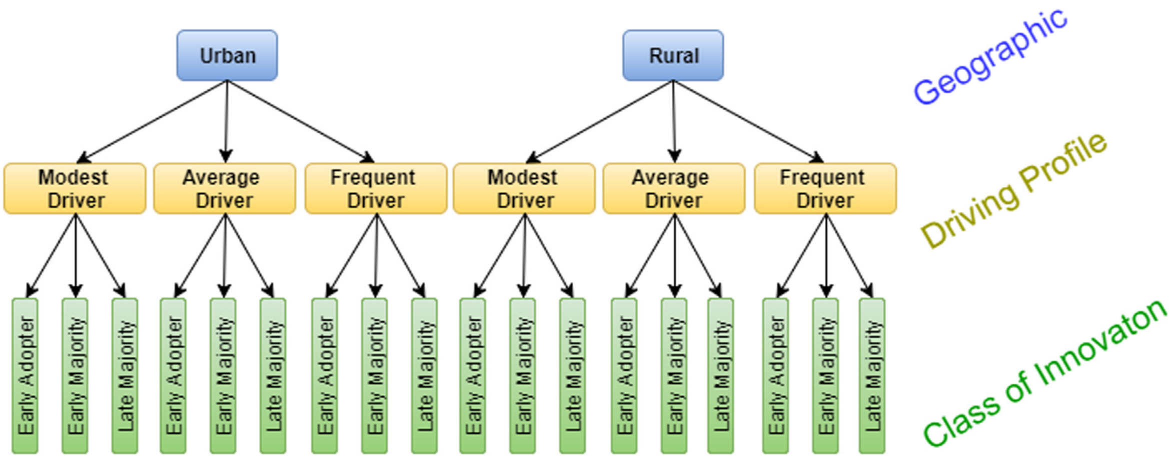

Fig. 3. Consumer choice model segmentation.

Table 1
Vehicle categories and classifications.[a]

Vehicle classification	Ireland		Denmark	
	Engine size	Mileage (km/yr)	Engine size	Mileage (km/yr)
Small	< 1300 cc	14,102	< 1400 cc	14,257
Medium	1300–1700 cc	19,257	1400–2000 cc	18,263
Large	> 1700 cc	24,339	> 2000 cc	22,714

[a] Data for Ireland for these classifications were collected from the National Car Test, which all private cars beyond four years old are obliged to take, and whereby the annual mileage of each tested vehicle is recorded. Data for Denmark has been obtained combining the inspection data of the Danish Road Directorate with the Administrative Car Register.

class of innovation (Early Adopter, Early Majority, Late Majority), as shown in Fig. 3.

The geographical split is made in accordance with the latest EU urban-rural typology (Eurostat, 2014). The driving profile segmentation is split by consumers with an average annual mileage of 15,000 km (modest driver), 20,000 km (average driver) and 25,000 km (frequent driver). A correlation between annual mileages and engine size (in cc's) was found in both Ireland and Denmark, whereby larger engine sizes were associated with larger annual mileages, while smaller engine sizes were associated with smaller annual mileages.[2] Therefore, technologies were categorised to correspond with these driving profiles (see Table 1) and the four ICE technologies considered (petrol, diesel, hybrid, PHEV) were split into 3 further bands: small (< 1300 cc), medium (1300 cc-1700 cc), and large (> 1700 cc), while BEVs were also split into 3 bands based off their range (< 125 km, 125–175 km, and > 175 km).

The classes of innovation are split by age groups, based on the synthesis of findings from the review of SPSs in Wilson et al. (2014) which found that: "*Respondent age was consistently reported as significant in AFV choice with younger people more likely to choose different types of gas, electric, biofuel, and fuel cell vehicles*". The age groups were chosen from the census population data of number of people with eligibility to drive and split geographically into the groups of < 35 years (early adopter), 35–65 years (early majority) and > 65 years (late majority), as the share of these groups relative to the driving population were found to roughly correspond with the market share of Roger's innovation classes (Rogers Everett, 1995). It should be noted that other studies indicate that classes of innovators are represented by a wide-ranging set of characteristics. For example, Axsen et al. (2016) identify early adopters of plug-in electric vehicles in Canada as relatively higher income earners, which is understandable as in general plug-in electric vehicles are currently more expensive than their ICE counterpart. There are many other potentially determining factors such as environmental awareness, marital status, number of children, and type of employment. In an idealised study, each of these parameters would be used to classify the innovation propensity amongst consumers. However, this study relied purely on revealed preference data to calibrate the models used, and this level of information was not available for the geographical and driver profiling selected and hence the authors relied on the simplified assumption of associating age with class of innovator.

The remainder of this section discusses the sources of tangible costs, intangible costs, and provides a detailed modelling framework for the stock simulation model used.

3.1.1. Tangible costs

The total tangible costs – capital cost, operation and maintenance cost and fuel cost - were collected from a variety of publicly available national statistic sources for both countries. Historical data for each cost component were available for Ireland over the period 2004–2015 and in Denmark over the period from 1986 to 2015 for all data with the exception of purchasing cost, which was only available at a technology specific level until 2008 and so held constant until 2015. A summary of all cost components, corresponding value ranges, and sources are presented in Table 2, with a graphical summary of all tangible costs for the 15 technologies within the scope of this study shown in Fig. 4. A list of all data used to calibrate the model for the Irish and Danish models can be found in the Supplementary Information attachment to this article.

3.1.1.1. Projections of variables. Projections of vehicle capital costs are taken from Argonne National Lab's vehicle system simulation tool, Autonomie (Moawad et al., 2016), which has been used to compare a large number of powertrain configurations and component technologies. According to this model, the price of conventional ICEs are expected to increase due to measures required to improve vehicle fuel efficiency through light weighting, which is accompanied by an increase in the cost of materials such as aluminium or carbon fiber. An expected decrease in the cost of battery production and deployment results in a fall in the price of AFVs. A summary of these cost projections indexed against 2015 is shown in Fig. 5, and further insights into Autonomie's modelling framework can be found in Moawad et al. (2016).

The tax systems in place in the base year is held constant to 2050, although scenarios are later formed through the derogation of these taxes. Annual fuel costs are determined as a product function of annual mileage, technology efficiency, and pump fuel prices, with variances in the annual cost of fuel for each consumer segment expected as both technology efficiency and fuel prices change. Fuel price changes for both countries were based on projections of the increase in fossil fuel import prices from Capros et al. (2013),

[2] It should be noted that this assumption does not hold true for all consumers, i.e., some owners of a small sized engine car may drive much more than 15,000 km and owners of a large sized engine car may drive sparingly. However, the overall average trend of the available data indicated the adopted assumption stated here and was used as the best-found method of accounting for driving profiles through empirical data.

Table 2
List of tangible costs in Ireland and Denmark, 2015.

Tangible cost variable	Cost components	Ireland value range (2015€)	Ireland sources	Denmark value range (2015€)	Denmark sources
	Purchasing cost excluding taxes	€11,512–50,054	SIMI (2017)	€7368–54,126	FDM (2017a)
Capital cost	VRT	Based on CO_2 emissions (14–36% of the open market selling price)	ACEA (2017)	105% of first €10,800 of the dealer's sales price and 180%* of the remainder, with reductions based on fuel economy and traffic safety equipment	ACEA (2016)
	VAT	23% of basic price of vehicle before VRT	Revenue (2015)	25% of the dutiable value at the time of their acquisition in new condition	ACEA (2017)
	Subsidy	€7500–10,000	Department of Finance (2017)	€59,003–90,785	Skatteministeriet (2015)
Operation and maintenance cost	Annual motor tax	Based on CO_2 emissions (€120–2350/yr)	ACEA (2017)	Based on fuel economy (€34–4186/yr)	Skatteministeriet (2017)
	Insurance	€1003–1757	AA (2015)	€981–1295	FDM (201b)
Fuel cost	Fuel price	€1.53/ltr – Petrol €1.45/ltr – Diesel €0.10/kWh - Electricity	AA (2017)	€1.50/ltr – Petrol €1.27/ltr – Diesel €0.23/kWh - Electricity	Country Economy (2017)
	Vehicle efficiency	6.66–0.91 L/100 km	Dineen et al. (2014)	8.48–0.91 L/100 km	FDM (2017a)

* This value changed to 150% in 2016 (European Automobile Manufacturers Association, 2017).

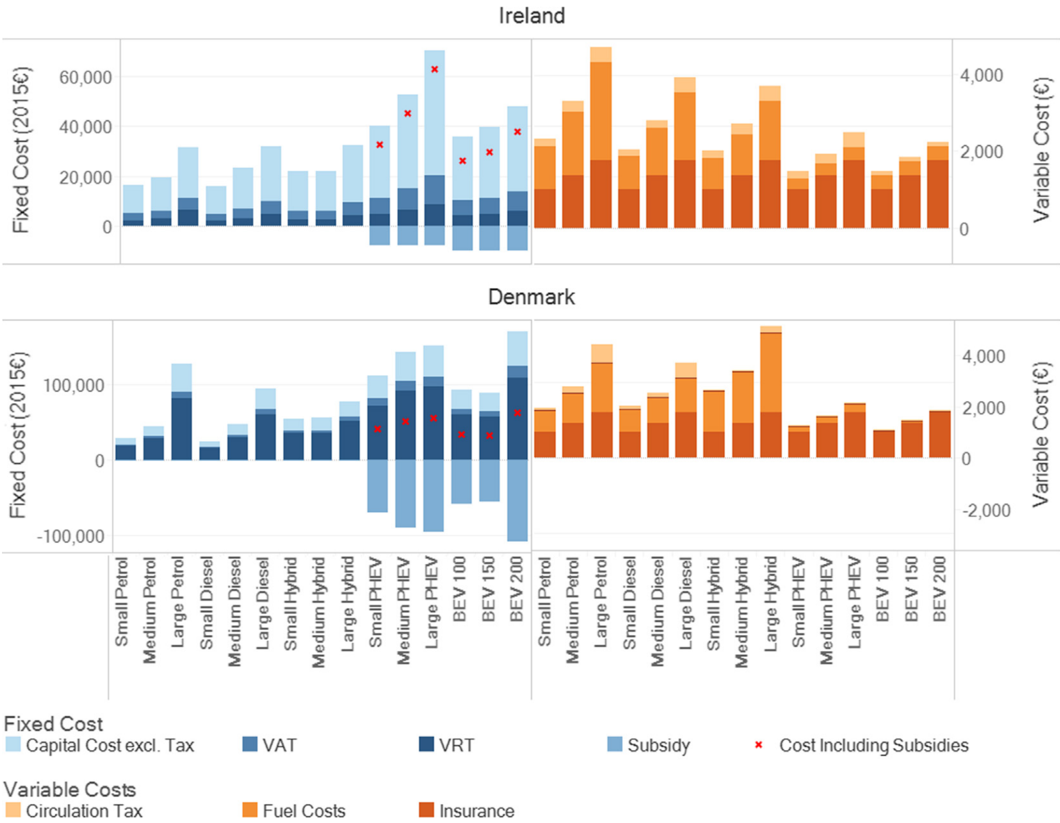

Fig. 4. Tangible costs in 2015 of all the 15 technologies included in the scope of analysis.

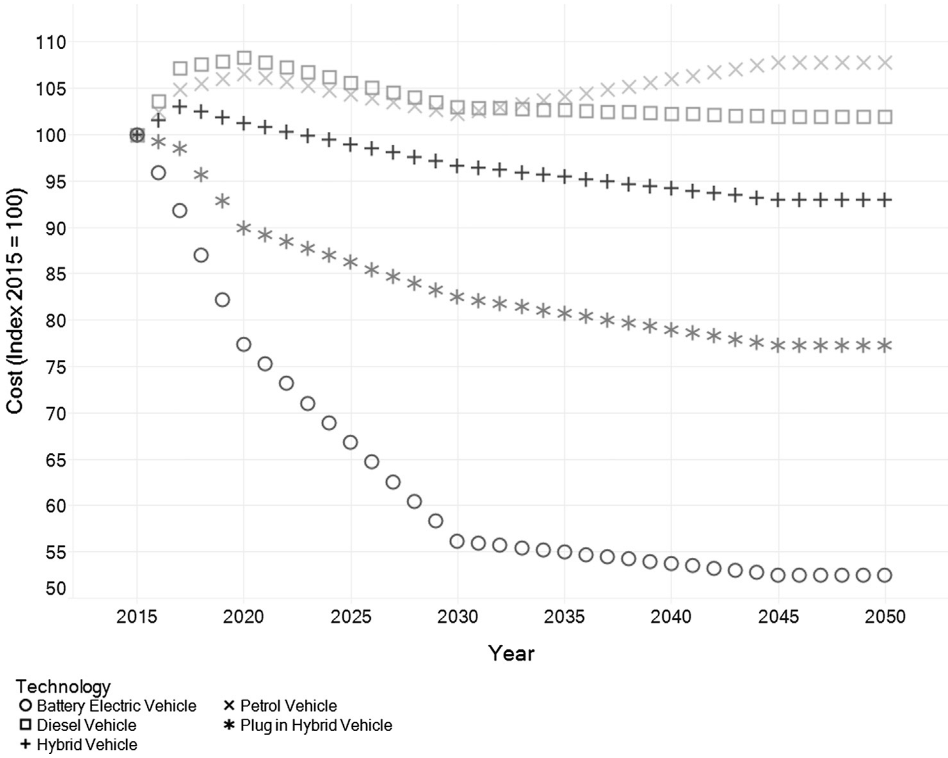

Fig. 5. Assumed projections of the tangible costs of the vehicle categories in 2015–2050.

while the improvements in vehicle energy efficiency were aligned with current European mandated manufacturer standards (European Parliament, 2009), and assuming maximum efficiency improvement by 2050 aligned with (IEA, 2008). Mileages were held constant from the base year.

3.1.2. Intangible costs

The role of intangible costs in these consumer choice models is to represent the non-monetary costs associated with vehicle purchasing as to draw a comparison between these intangible costs and the actual costs faced by consumers (tangible costs). Intangible costs have been introduced into consumer choice models as a means of providing more accurate competition between technologies in the past, e.g., (Bunch et al., 2015; Kamiya, 2015; McCollum et al., 2016). This subsection identifies the means through which this study monetises the main intangible.

3.1.2.1. Model availability/risk related disutility. Empirical data were used to determine the intangible costs associated with model availability and risk related disutility across all technology classes and consumer segments based off the number of models of vehicles available for sale. While no regional disparity is used for these costs, as it is assumed that the vehicle market is heterogeneous for both urban and rural areas, intangible costs are assumed to vary for consumers of varying driving profiles and adoption propensity. These intangible costs are applicable for all vehicles: a low representation of models available for a class of ICEs will pertain to a high intangible cost, as it would for AFVs. This approach allows the model to account for a potential fall in the availability of ICEs over time, which would then generate higher disutility costs for these technologies perceived by consumers. Vice versa, a rise in the number of AFVs available for sale would result in lower perceived disutility costs. The primary difference between ICEs and AFVs in this respect relates to the current standing of the market, which is currently dominated by diesel and petrol ICEs in both Ireland and Denmark, indicating that these vehicles are at the latter stage of the diffusion of innovation curve (low relative risk related disutility), while AFVs are at an early stage (high relative risk related disutility). This section first discusses the methodology adopted in line with this logic to introduce a model availability disutility cost for both ICEs and AFVs.

3.1.2.1.1. ICE model availability disutility. The competition between ICEs in a market independent of AFVs was initially analysed to determine the disutility cost associated with model availability for the late majority consumer segment – this study assumes that ICE vehicles are at the latter stage of Rogers' diffusion curve, and are thus assumed to represent the late majority consumer segment. The share of AFVs sold in both Ireland and Denmark over the period analysed was 0.08% and 0.19% respectively, and thus assumed to have had a negligible impact on consumer choice of ICEs. As first discussed in Section 3, different consumer driving profiles relate to different sizes of vehicles in both countries. Therefore, the intangible cost related to model availability for modest drivers, average drivers, and frequent drivers is determined by the available number of small sized cars, medium sized cars, and large sized cars respectively.

A non-linear intangible cost function depicting model availability was introduced and calibrated using the historic market share as a bench mark. The intangible cost relating to model availability varies by the number of models for each technology available, whereby a low number of a certain technology yields a high intangible cost, and vice versa (see Eq. (3)). Calibration of this function involved minimising the residual square error between the predicted and actual sales across each driving profile by varying the constants α and β for each driving profile (DP) within the Late Majority (LM) consumer segment. The values for these constants, along with the R^2 values when comparing the historic market share to that calculated by the consumer choice model after incorporating these generalised cost parameters is given in Table 3.

$$Model\ \ Availability\ \ Intangible\ \ Cost_{LM,DP} = \frac{\alpha_{DP}}{\beta_{DP} + No.\ \ Models\ \ Available_{DP}} \tag{3}$$

The number of models available for sale in Ireland between 2004 and 2015 of each technology is taken from the Society of the Irish Motor Industry (SIMI, 2017), as with the data for capital costs, while for Denmark a comprehensive list of models available from 1986 to 2008 is gathered from (FDM, 2017a). No comprehensive list of models available for sale was found for Denmark beyond 2008, so the number of different technology types sold (available from EEA, 2017) is used as an indicator for the rate of change in the model availability to 2015. The consumer choice model results with and without these cost curves are shown in Fig. 6.

It was deemed necessary to include these intangible costs as they enabled a stronger calibration of the model, shown in Fig. 6, and provided a high R^2 value across each driving profile.

3.1.2.1.2. AFV model availability and risk related disutility. The nature of a risk related disutility, which has been adopted by this

Table 3
Generalised cost curve parameters and corresponding R^2 for the frequent drivers consumer segment.

		Modest driver	Average driver	Frequent driver
Ireland	α	1.86E+05	2.16E+05	1.60E+06
	β	27.27	0.00	0.00
	R^2	**0.998**	**0.899**	**0.832**
Denmark	α	1.39+E06	1.51+E06	1.13+07
	β	192.87	119.75	439.67
	R^2	**0.986**	**0.986**	**0.788**

All values in bold have a significance level of < 0.001.

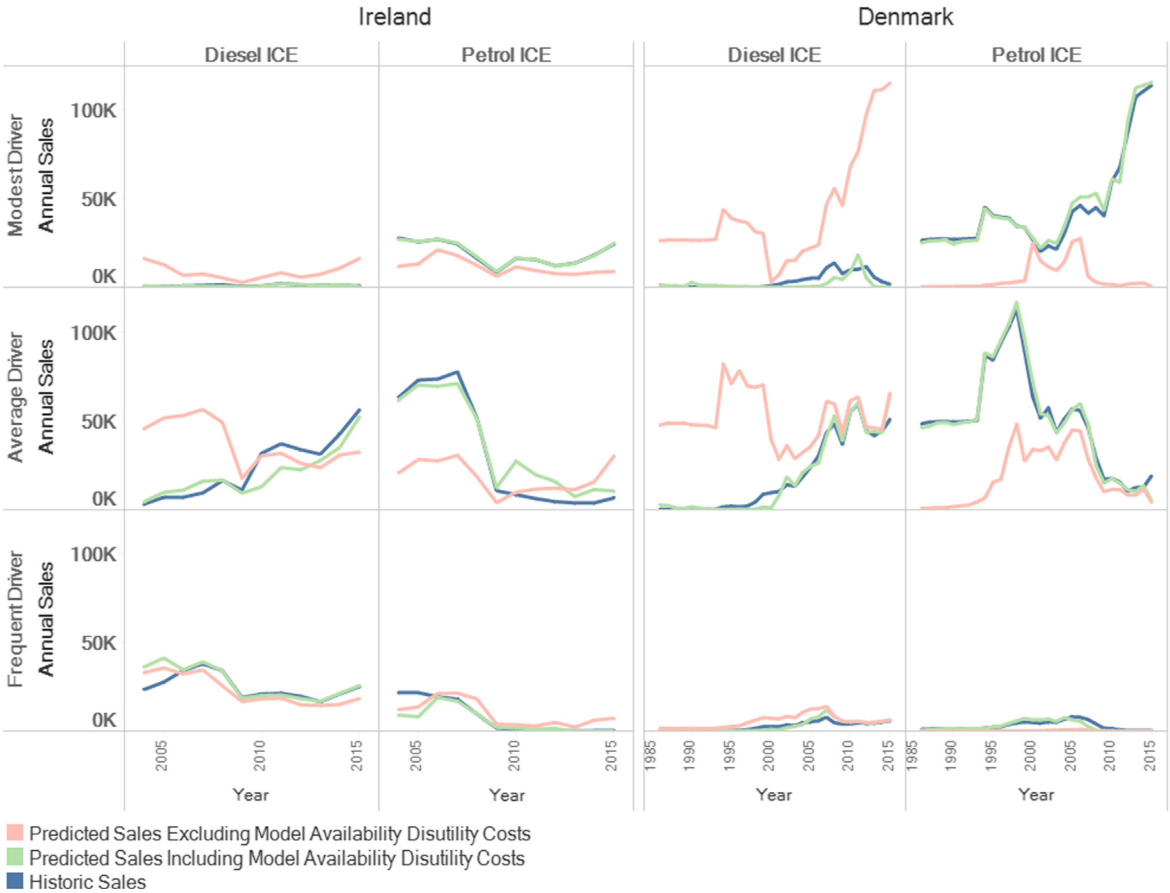

Fig. 6. Consumer choice model results for ICE vehicles, with and without model availability disutility costs.

study, accounts for the varying level of perceived risk within each consumer segment - early adopters associate a lower risk with the purchase of an AFV relative to that associated by the late majority. In an attempt to monetise this risk using quantitative data, this study created a non-linear regression model to analyse the variance in intangible costs of AFVs with respect to the number of models available for sale across the EU-28 using the publicly available database from the Environmental Energy Agency (EEA) on vehicle sales from 2010 to 2015. Vehicle sales figures from these databases were extracted and used as an input for a European consumer choice model (using Eq. (2)), with the same structure as that of the Irish and Danish consumer choice models, to determine the intangible costs for consumers of AFVs within each of the 28 EU member states. Technologies were segmented to align with those used in the Irish and Danish consumer choice model, and tangible costs were calculated using the vehicle cost excluding taxes from the Irish and Danish databases, with the varying level of tax rates for each member state calculated according to ACEA (2015). The generalised intangible costs for AFVs were then generated to align with market shares in each country in each year from 2010 to 2015. While the purpose of these databases was to show compliance with European emission standards, this study found a large number of discrepancies with the reporting of fuel types within the database. For example, in 2015 12,000 Citroen ICEs were wrongly reported as either 'petrol and electric' or 'diesel and electric' and subsequently published as PHEVs by the EEA. Furthermore, a large number of hybrids have been reported by the EEA as PHEVs. In 2015, the EEA reported 126,000 PHEVs sold in Europe, although after manually correcting misreported fuel types within these EEA databases, the actual sale of PHEVs in 2015 was found to be 82,412. In the 2016 release of this database, no further discrepancies were found.

Finally, a non-linear regression analysis was carried out using these intangible costs as dependent variables and using the number of AFVs available for sale within each country, extracted from EEA (2017) as explanatory variables. Eq. (4) was used to calculate the intangible cost pertaining to model availability for the early adopter (EA) consumer segment for different vehicles (ve). The parameters of this equation were generated from the regression discussed above, as it makes the assumption that all consumers of AFVs so far fall within the early adopter segment. To generate the parameters for the early majority segment, interpolation was carried out between the early adopter and late majority generalised cost curves. These factors are presented in Table 4.

$$Model\ Availability\ Intangible\ Cost_{EA,v} = \frac{1}{C_{0_{ve}} + C_{1_{ve}} * No.\ \ Models\ Available_{ve}} \tag{4}$$

Table 4
Generalised cost curve parameters for the early adopter and early majority consumer segments.

Technology	Constant	Early Adopter	Early Majority (Interpolated)
BEV_100	C_0	7.70E−04***	3.85E−04
	C_1	5.49E−05	2.98E−05
BEV_150	C_0	4.27E−04***	2.14E−04
	C_1	3.19E−05***	1.83E−05
BEV_200	C_0	8.52E−05***	4.26E−05
	C_1	8.88E−06***	6.75E−06
PHEV small	C_0	1.10E−04	5.50E−05
	C_1	3.38E−05***	1.98E−05
PHEV medium	C_0	6.11E−05	3.05E−05
	C_1	1.96E−05***	1.21E−05
PHEV large	C_0	1.22E−05	6.09E−06
	C_1	5.46E−06***	4.48E−06

*** Statistical significance at the $p < 0.001$ level.

3.1.2.2. Range anxiety/refuelling infrastructure. Range anxiety is defined in this study as the perceived disutility faced by a consumer in failing to meet a desired travel demand due to shortages in battery charge availability. As a form of proxy, this study first attempts to consider the variation in intangible costs for all 28 EU member states compared against the variation in charging point availability, with the logic that range anxiety falls as the number of charging points rise. A regression was established to consider this variation using the intangible costs (determined in Section 3.2 above) and the number of public charging points available from ACEA (2017). This regression, however, was found to have a low level of significance, concluding that there was an insufficient level of information relating to private charging points (such as work and home charge points).

Therefore, this study employs a similar approach as used by McCollum et al. (2016), whereby the daily travel profiles of each consumer segment are calculated using the gamma distribution curves generated by the MA^{3}T model, and the failure to meet the daily travel demand on one day ensues a penalty. The penalty used to encompass both range anxiety and refuelling infrastructure is chosen by calibrating the model results to national sales in 2015 and decreases linearly to the cost of renting a vehicle (€117.89 for Ireland and €186.04 for Denmark[3]). The probability of BEV drivers meeting their daily travel demand is based on the number of charge points available (either a type 2 home charger, a type 2 work charger, or both) and the time spent charging (8 h at home, 7 at work). All BEV drivers are assumed to have access to at least one private charging point, and introducing a second charging point reduced range anxiety.

3.2. CarSTOCK model

The market shares are an output from the consumer choice model into a technology-rich private car sectoral simulation model to calculate the final stock, energy consumption, and emissions for both Ireland and Denmark. The original CarSTOCK Model (see Daly and Ó Gallachóir, 2011b) relied on assumed market shares of each technology while this paper expands on this approach by creating a hard-link between the consumer choice model and the CarSTOCK model. This link enters the calculated market shares for each of the 15 technologies into the CarSTOCK model which then executes calculations on stock, energy, activity, and emissions.

The Irish and Danish CarSTOCK models draw upon detailed national data statistics relating to the composition of the market, sales, average mileage, efficiency, and life-time of vehicles with a disaggregation of vintage, fuel type and engine size to produce a long-term evolution of the private car stock, energy use and related CO_2 emissions to 2050 based off the ASIF methodology developed by Schipper et al. (2000) which can be summarised by Eq. (6). In brief, total private transport related CO_2 is calculated as a sum of the product of vehicle activity (A), private car stock (S), energy intensity (I), and emission factors (F) for fuel type (f) and vintage (vi). Projections of total activity and total stock are calculated endogenously within the CarSTOCK model, using gross national product (GNP) and fuel prices, linked with literature based elasticities of demand, as drivers.

$$Transport\ \ Related\ \ CO_2 = \sum_{f,vi} A_{f,vi} * S_{f,vi} * I_{f,vi} * F_f \tag{5}$$

Aggregate emissions for the private transport sector is calculated in this manner for each of the 15 technologies analysed. This model uses the structure of the Irish CarSTOCK model, which was originally developed for policy analysis in the area of private transport (Daly and Ó Gallachóir, 2011b) and has been updated using recent national data on an annual basis. This structure is replicated for Denmark using detailed national statistical data.

Activity is recorded in an annual vehicle inspection for both countries, whereby the annual mileage of each vehicle in the country is recorded. This data was accessed through the Sustainable Energy Authority of Ireland (SEAI) who processed this raw data into technology specific data, and from accurate odometer readings from the Ministry of Transport (MOT) tests for Denmark.

Stock data in Ireland is obtained from the Vehicle Registration Unit, who provides a detailed list of vehicles, accounting for fuel

[3] Prices for Denmark and Ireland were based off 54 and 85 quotes respectively from 5 different car rental companies.

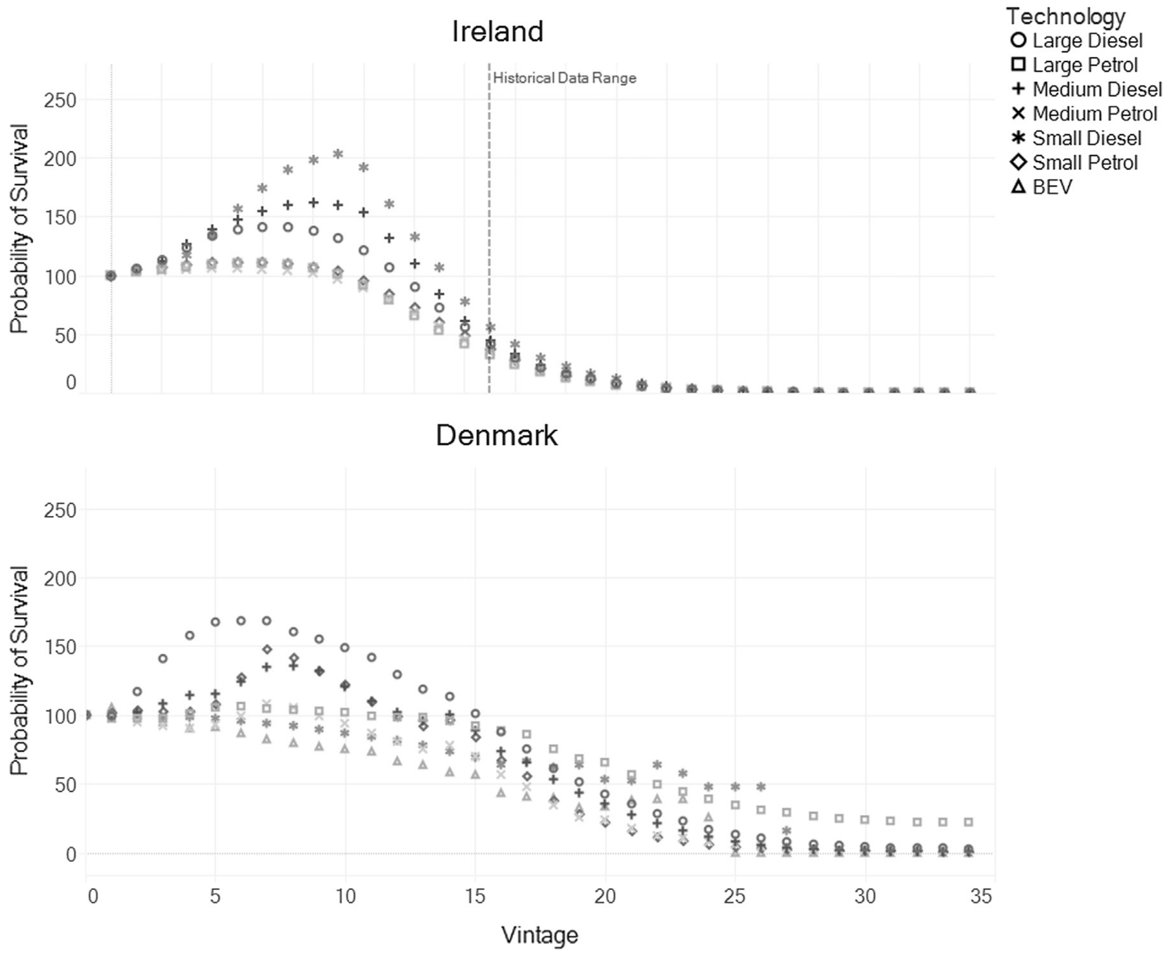

Fig. 7. Irish and Danish technology survival profiles.

type, engine size (ES) and vehicle vintage (vi). This data for Denmark is obtained combining the inspection data of the Danish Road Directorate with the Administrative Car Register. As this paper has previously shown that diverse technologies have different driving profiles (see Section 3, Table 1), it can be assumed that there is a variation in the level of deterioration for each technology. For this reason, a survival profile is built to account for an accurate lifetime of each vehicle type using this information in tandem with Eq. (5). The resulting probability of survival is presented in Fig. 7.

$$Survival\ Rate_{vi}^{ES} = Average\left(\frac{(Stock_{vi}^{ES} - Stock_{vi-1}^{ES})}{Stock_{vi}^{ES}}\right) * (1 + Survival\ Rate_{vi-1}^{ES}) \tag{6}$$

The oldest data available for Ireland was from the year 2000, resulting in survival profiles up to the age of 16 years being built. Data beyond this was extrapolated using an exponential decay in line with historic data. Data for Denmark was available since 1985.

Specific energy consumption of the historic fleet in Ireland disaggregated by engine band are obtained from the SEAI, who links national sales data of each vehicle to the manufacturer's specified energy consumption per km. Efficiency data for Denmark has been obtained combining the inspection data of the Danish Road Directorate with the Administrative Car Register. A comparison of the specific energy consumption of each vehicle type is shown in Table 5.

The fuel emission factors for petrol and diesel were taken from Dineen et al. (2014). Relating to electricity emissions, both Ireland and Denmark have made recent strides towards a low carbon power sector, aiming for 40% and 50% renewable electricity by 2020 respectively (DCCAE, 2010), (Danish Energy Agency, 2015). Projections of electricity specific CO_2 emissions were taken from the EU PRIMES reference scenario, which assumes an emissions intensity in 2050 of 0.03 tCO_2/MWh in Denmark (down from 0.17 tCO_2/MWh in 2015) and 0.13 tCO_2/MWh in Ireland (down from 0.41 tCO_2/MWh in 2015) (European Parliament, 2016).

The drivers of the stock model, namely fuel price and GNP, are chosen following the methodology carried out in the original development of the Irish CarSTOCK model (Daly and Ó Gallachóir, 2011a) and replicated for Denmark. Projections of GNP are generated using the Economic and Social Research Institute long-term macro-economic model HERMES results from the Medium term review, 2013 (Bergin et al., 2013) and taken from OECD national projections for Danish projections. These projections are then linked with income and fuel elasticities of demand derived from Johansson and Schipper (1997) to generate projections of stock and

Table 5
Specific energy consumption by class of car technology for Ireland and Denmark in 2015.

Specific energy consumption (MJ/km)	Ireland	Denmark
Small petrol	1.83	1.45
Medium petrol	2.22	1.77
Large petrol	2.70	2.73
small diesel	1.60	1.15
Medium diesel	1.62	1.25
Large diesel	2.19	1.82
Small hybrid	1.38	1.38
Medium hybrid	1.37	1.37
Large hybrid	1.89	1.89
Small plug in hybrid	0.68	0.29
Medium plug in hybrid	0.68	0.69
Large plug in hybrid	0.77	1.00
Battery electric vehicle	0.64	0.62

activity (see Table 6).

4. Results and discussion

The consumer choice model produced satisfactory results of vehicle market shares for both the base year (2015) and first year of available data in both Ireland and Denmark (2004 and 1986 respectively). The resulting market share for both Ireland and Denmark in 2015, with and without intangible costs, are shown in Fig. 8. The results highlight the importance of accounting for the non-monetary parameters in order to have a reliable model.

In keeping with the original aim of this study - which sets out to determine the effect of revoking tax relief for BEVs and PHEVs, and to determine the cost and effectiveness of implementing further governmental level policy measures incentivising BEV and PHEV purchasing - the scenarios are set in a similar fashion. Firstly, a Business as Usual scenario (BaU) identifies the change in stock, emissions, and energy consumption from the base year to 2050 following a retraction of BEV and PHEV subsidies in line with currently national government policies in Ireland and Denmark. This scenario is developed upon whereby the impact of reducing the model availability of BEVs and PHEVs through increasing the number of models available for sale is explored. Secondly, multiple scenarios identifying the impact of government intervention, in tandem with external factors (i.e., beyond the control of national governance) are explored. These policy-induced interventions range from the reintroduction of a VRT subsidy for BEVs and PHEVs, introduction of a derogation of VAT for BEV and PHEVs, offering free electricity for vehicle charging, a derogation of the annual motor tax (AMT) for BEVs and PHEVs, and a regulation of the sales of ICEs. The external factors explored detail the varying level of BEV and PHEV vis-à-vis varying the number of models available – as neither Ireland nor Denmark produce automobiles, they must rely on foreign manufacturers to produce more BEV or PHEV models to reduce the model availability intangible cost. Finally, the cost and corresponding market uptake associated with the introduction of these monetary controlled incentives are presented.

The remainder of this section summarises the market shares calculated by the consumer choice model and the resulting final stock and emissions figures under these scenarios. These results represent the combination of the 18 consumer segments, but are the representation of the entire national market. Fig. 9 presents the various costs within the consumer choice model for one specific consumer segment - the urban, modest driver, early adopter segment for Ireland under a BaU. In this sample scenario, the capital costs for ICEs increase and the capital cost for BEVs and PHEVs decrease, while the model availability intangible costs for BEVs and PHEVs reduce due to a linear increase in the number of models available for sale. These changes in costs increase vehicles competitiveness within the model and increase the market share for AFVs. Each segment is calculated individually and later combined to give a comprehensive representation of the national car stock market.

4.1. VRT subsidy removal – BaU

4.1.1. Ireland

Under a BaU with no variation in the number of models available for sale, the market share of BEVs in Ireland rises from 0.39% in the base year to 1.2% in 2021, then falling to 0.3% once the VRT subsidy is removed in 2022. This market share then rises steadily to 4.5% by 2050, driven by the assumed reductions in the cost of BEVs and cost increases in ICEs (Moawad et al., 2016). The market share of PHEVs largely goes unchanged. The market share in the base year stands at 0.002% of all vehicles bought, and following the

Table 6
Fuel price and income elasticities of demand.

Elasticities of demand	Stock	Vehicle kilometres
Fuel price elasticity	−0.1	−0.1
Income elasticity	0.35	0.6

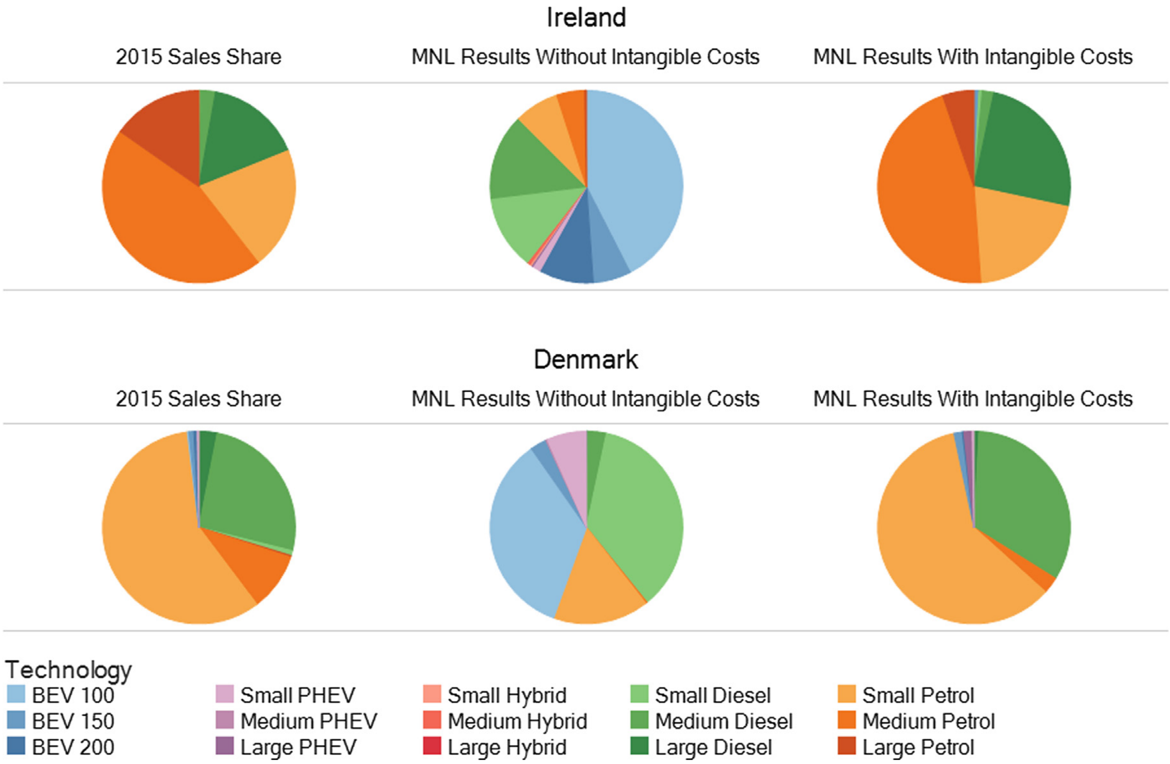

Fig. 8. Historic and model market shares for Ireland and Denmark for 2015.

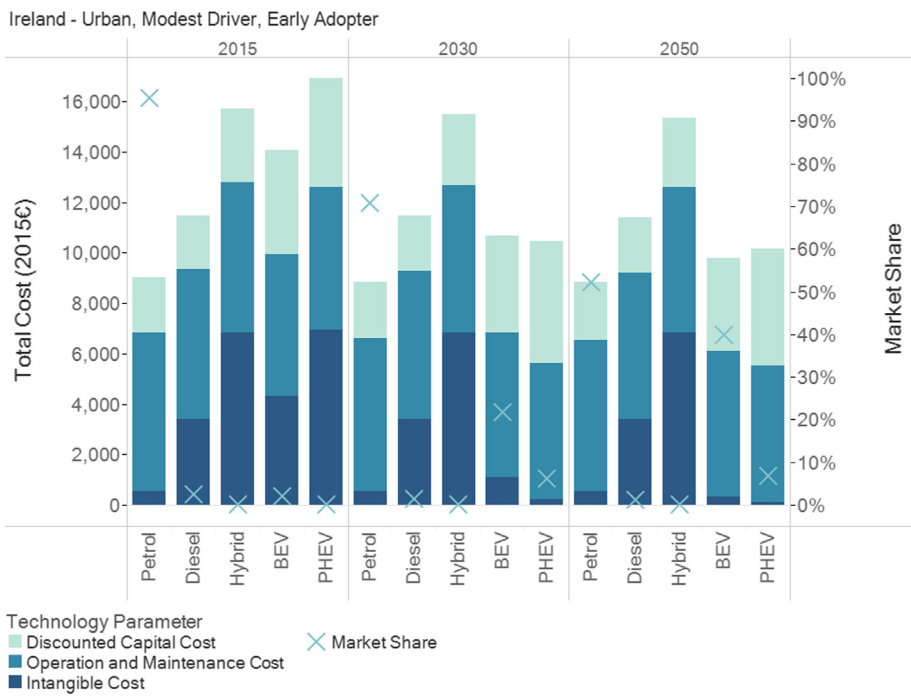

Fig. 9. Market share and associated costs for BaU with an increase in BEV/PHEV models available.

removal of the VRT subsidy in 2019, this is reduced to 0.001%. Despite reductions in the cost of this technology, there is no change in the market share by 2050 due to the low level of PHEV models available. Total AFV stock reaches 91,000 vehicles by 2050, with 3.46 million ICEs.

Emission reductions are still evident despite the low uptake of AFVs driven by ICE efficiency improvements. These efficiency improvements are in line with current European standards of manufacturer's achieving a maximum of 95gCO_2/km per vehicle produced by 2021 (European Parliament, 2009) and a regulatory proposal of setting this standard to between 68 and 78 gCO_2/km for 2025 (Mock, 2013). Efficiency improvements beyond this are assumed at a year-on-year value of 0.75%, in line with the total long-range potential efficiency improvements of ICEs by 2050 according to IEA (2008). These efficiency improvements coupled with the marginal electrification of transport provide a 19% reduction in well-to-wheel CO_2 emissions by 2050 relative to 2015.

4.1.1.1. Sensitivity due to model availability. A linear increase in the model availability of BEVs and PHEVs from their current standing to match the number ICE models currently available reduces the intangible costs for these technologies significantly and by 2050 increases their combined market share to 49%. This corresponds to approximately 1.4 million BEVs and 75,000 PHEVs in the private vehicle stock by 2050, and a 44% reduction in well-to-wheel CO_2 emissions relative to 2015.

4.1.2. Denmark

The initial retraction of the VRT subsidy in 2016, whereby BEV/PHEV consumers must pay 20% of the tax payable, sees a sharp fall in total market share of these vehicles, from a combined 3.2% in 2015 to 0.7% in 2020 when the subsidy is completely removed. The assumed improved efficiency within ICE vehicles increases competitiveness due to lower fuel costs, which in tandem with the assumed changes in the technology costs contributes to a marginal increase in market share of BEVs and PHEVs to a combined value of 1.7% in 2050. Total AFV stock reaches approximately 50,108 vehicles in 2050, while ICEs retain the lion's share at 3.64 million vehicles. Similar to the Irish results, this AFV penetration combined with the assumed efficiency improvements in ICEs generates an 18% reduction in well-to-wheel CO_2 emissions by 2050 relative to 2015, despite a 54% increase in total national vehicle stock over the same time period.

4.1.2.1. Sensitivity due to model availability. Increasing the number of AFV models available for sale to match that of ICEs in 2015 by 2050 results in a low increase in the market share of both BEVs and PHEVs, rising to 2.7% in 2050. This corresponds to a stock of 88,574 AFVs in 2050, and a reduction in well-to-wheel CO_2 emissions of 19% by 2050 relative to 2015. The uptake of AFVs is significantly lower than that of Ireland due to the significant rise in costs of EVs and PHEVs following the retraction of the VRT subsidy.

4.2. Governmental policy levers

The purpose of policies which act in favour of AFVs are, in general, to incentivise the sale of a new technology to a point where they overcome the initial barriers associated with purchasing and begin to achieve a greater market share. If incentives are drawn back too soon, they can prove ineffective. If incentives remain for too long, they may prove overly expensive. For this reason, 3 targets are set – achieving a 10%, 50% and 80% market share penetration. In each of these scenarios, once the market share is achieved, the subsidy is ceased. Values marked with an asterisk in Table 7 signify success in meeting this target, while other figures represent a failed target. The scenarios for this analysis are divided into both monetary policy levers – offering a derogation of VRT, VAT, AMT, and offering free fuel for AFVs – and non-monetary policy levers – banning the sale of ICEs in 2030 with a 5 year phase in period. This latter policy lever is chosen to be in line with the Irish stated national ambition that by 2030 all new cars and vans sold in Ireland will be zero emission capable (DTTAS, 2017), which roughly follows recent ambitions by France and the United Kingdom to ban the sale of petrol and diesel cars by 2040 (Department for Environment, 2017; Ministére de la Transition, 2017). An externality to the model is the number of AFV models available for sale, as both Ireland and Denmark are vehicle 'takers' rather than vehicle 'makers'. This attribute is classified into a 'low' scenario, where there is no change to the number of AFV models available, a 'medium' scenario, where by 2050 there are half of the number of AFV models available as there are currently ICEs, and a 'high' scenario, where the number of AFVs and ICE mo (Ministére de la Transition, 2017) dels available in 2050 is equal.

The monetary results in Table 7 represent the combined annual tax revenue foregone and cost of incentive (in the case of 'No Refuelling Costs') of that scenario relative to the BaU (see preceding section for definition). For this reason, the 'No Incentive' policy could still result in a loss to the exchequer as the taxes paid by AFV consumers are, in general, lower than that of ICEs. The percentages in Table 7 represent the WTW CO_2 emissions reduction relative to the base year.

Placing an early ban on the sale of ICEs was found to have the cost optimal impact on the uptake of AFVs, with the penetration target met in 88 of the 90 scenarios run. In the case when no incentives are offered, there is generally a loss in revenue relative to the BaU due to the relatively cheaper nature of AFVs. In the scenario without any incentive offered, a high AFV model availability and a ban on the sale of ICEs, the average annual loss in tax to the exchequer is €169.7 m/year in Ireland (resulting in an 89.3% AFV penetration) and €408.2 m/year (resulting in an 86% AFV penetration) in Denmark, where the relative higher loss in Denmark is due to the higher rates of tax. In some rare cases, there is a net gain in tax revenue (signified by a negative value in Fig. 10) due to the greater purchasing of AFVs close to the base year, when investment costs are relatively higher compared against ICEs which, in turn, yields a higher tax. In the case where no limit is placed on the sale of ICEs, the AFV target was achieved in just 25 scenario runs out of 90, with an 80% AFV penetration only met in 1 scenario (high availability of AFVs + VAT derogation in Ireland).

While all 90 scenario runs are presented in Table 7, Fig. 10 presents the market share and associated cost to the exchequer for four scenarios defined as follows:

i. S1 – Low AFV model availability, no ban on the sale of ICEs, no further incentives offered (BaU).

Table 7
Tax foregone/cost of incentive (in million 2015€ per annum) and% WTW CO_2 emission reductions in 2050 relative to 2015.

Country	Scenario		No ban on ICE sales			Ban on ICE sales by 2030		
			Low AFV model availability	Med AFV model availability	High AFV model availability	Low AFV model availability	Med AFV model availability	High AFV model availability
Ireland	10% AFV Target	No incentive	€0m/19.9%	_€101 m/54.4%_*	_€114.1 m/59.1%_*	_€162.3 m/68%_*	_€179.5 m/68.8%_*	_€169.7 m/69.5%_*
		VRT derogation	€24.2 m/20.5%	_€130.9 m/54.5%_*	_€147.1 m/59.1%_*	_€187.7 m/68%_*	_€207.1 m/69%_*	_€200.9 m/69.6%_*
		VAT derogation	€43.6 m/21%	_€141.3 m/54.6%_*	_€155.3 m/59.3%_*	_€202.6 m/68.1%_*	_€216.9 m/69.1%_*	_€208.6 m/69.8%_*
		AMT derogation	€1.5 m/20%	_€101.8 m/54.4%_*	_€114.5 m/59.1%_*	_€163.1 m/68%_*	_€179.6 m/68.8%_*	_€169.8 m/69.5%_*
		No refuelling costs	€6.4 m/20.6%	_€102 m/54.6%_*	_€112.9 m/59.2%_*	_€164.5 m/68%_*	_€178.5 m/69%_*	_€167.7 m/69.7%_*
	50% AFVs Target	No incentive	€0m/19.9%	_€101 m/54.4%_*	_€114.1 m/59.1%_*	_€162.3 m/68%_*	_€179.5 m/68.8%_*	_€169.7 m/69.5%_*
		VRT derogation	€24.2 m/20.5%	_€292.5 m/56.5%_*	_€302.6 m/60.6%_*	_€316.1 m/68%_*	_€339.1 m/69.3%_*	_€336.4 m/70%_*
		VAT derogation	€43.6 m/21%	_€391.5 m/57.2%_*	_€374.2 m/61%_*	_€399 m/68.1%_*	_€420.9 m/69.8%_*	_€400.8 m/70.6%_*
		AMT derogation	€1.5 m/20%	_€110.4 m/54.7%_*	_€121.8 m/59.3%_*	_€168.9 m/68%_*	_€185.2 m/68.9%_*	_€175.1 m/69.5%_*
		No refuelling costs	€6.4 m/20.6%	_€124.8 m/56.6%_*	_€130.9 m/60.6%_*	_€181.6 m/68.1%_*	_€194.6 m/69.3%_*	_€181.6 m/70%_*
	80% AFVs Target	No incentive	€0m/19.9%	€101 m/54.4%	€114.1 m/59.1%	€162.3 m/68%	_€179.5 m/68.8%_*	_€169.7 m/69.5%_*
		VRT derogation	€24.2 m/20.5%	€484.4 m/60%	€561.5 m/64.1%	_€535.5 m/68.1%_*	_€523.7 m/69.2%_*	_€520.8 m/70%_*
		VAT derogation	€43.6 m/21%	€748.7 m/62.6%	_€825.8 m/65.9%_*	_€733.8 m/68.1%_*	_€701.7 m/69.7%_*	_€705.8 m/70.6%_*
		AMT derogation	€1.5 m/20%	€114.9 m/54.7%	€130.4 m/59.4%	€179.2 m/68%	_€193.6 m/68.9%_*	_€183.6 m/69.6%_*
		No refuelling costs	€6.4 m/20.6%	€154.4 m/59.6%	€173.4 m/63.7%	_€211.5 m/68.1%_*	_€219.9 m/69.4%_*	_€206.7 m/70.1%_*
Denmark	10% AFV Target	No incentive	€0m/17.6%	€16.3 m/18.7%	€19 m/18.9%	_€105.8 m/76.4%_*	_€325.9 m/76.6%_*	_€433.8 m/76.7%_*
		VRT derogation	€165.9 m/19.3%	_€433.6 m/24.7%_*	_€452.9 m/24.9%_*	_€715 m/77.8%_*	_€718.3 m/78.4%_*	_€731.9 m/78.1%_*
		VAT derogation	€42.5 m/18.3%	€50.2 m/19.1%	€66.8 m/19.7%	_€402.4 m/76.6%_*	_€494.9 m/77%_*	_€582.6 m/77.1%_*
		AMT derogation	€0.9 m/17.6%	€16.6 m/18.7%	€19.4 m/19%	_€108.6 m/76.4%_*	_€326.7 m/76.6%_*	_€434.5 m/76.7%_*
		No refuelling costs	€3.7 m/17.7%	€13.6 m/18.7%	€16.6 m/19%	_€296.3 m/76.4%_*	_€465.9 m/76.7%_*	_€555.7 m/76.7%_*
	50% AFVs Target	No incentive	€0m/17.6%	€16.3 m/18.7%	€19 m/18.9%	_€105.8 m/76.4%_*	_€325.9 m/76.6%_*	_€433.8 m/76.7%_*
		VRT derogation	€165.9 m/19.3%	_€1,761.7 m/51.6%_*	_€1,865.5 m/53%_*	_€1382 m/77.8%_*	_€1,462.7 m/81%_*	_€1,475.3 m/81.3%_*
		VAT derogation	€42.5 m/18.3%	€50.2 m/19.1%	€66.8 m/19.7%	_€589.8 m/76.6%_*	_€705.4 m/77.1%_*	_€766.2 m/77.2%_*
		AMT derogation	€0.9 m/17.6%	€16.6 m/18.7%	€19.4 m/19%	_€109.8 m/76.4%_*	_€328.1 m/76.7%_*	_€435.9 m/76.7%_*
		No refuelling costs	€3.7 m/17.7%	€13.6 m/18.7%	€16.6 m/19%	_€274.7 m/76.4%_*	_€444.2 m/76.7%_*	_€533.9 m/76.7%_*
	80% AFVs Target	No incentive	€0m/17.6%	€16.3 m/18.7%	€19 m/18.9%	_€105.8 m/76.4%_*	_€325.9 m/76.6%_*	_€433.8 m/76.7%_*
		VRT derogation	€165.9 m/19.3%	€2,009.1 m/59.5%	€2,323.8 m/65.4%	_€2219 m/77.7%_*	_€2,378.5 m/81.3%_*	_€2,418.8 m/81.7%_*
		VAT derogation	€42.5 m/18.3%	€50.2 m/19.1%	€66.8 m/19.7%	_€797.1 m/76.6%_*	_€924.7 m/77.1%_*	_€1009.2 m/77.3%_*
		AMT derogation	€0.9 m/17.6%	€16.6 m/18.7%	€19.4 m/19%	_€111.3 m/76.4%_*	_€330.9 m/76.7%_*	_€438.7 m/76.7%_*
		No refuelling costs	€3.7 m/17.7%	€13.6 m/18.7%	€16.6 m/19%	_€222.1 m/76.4%_*	_€383.1 m/76.7%_*	_€475.9 m/76.7%_*

Italicised text with an "*" signifies that the AFV target was met in the given scenario.

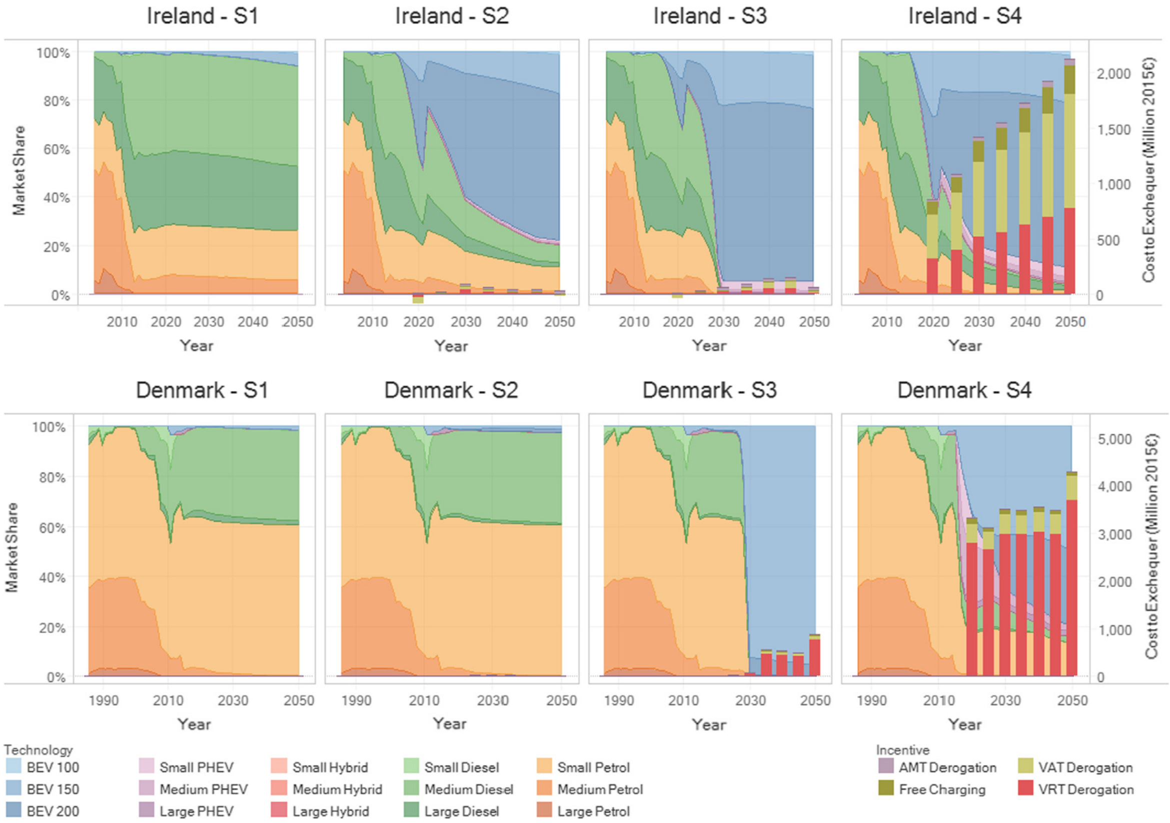

Fig. 10. Market Share and annual cost to the Exchequer for select scenarios from the consumer choice model.

ii. S2 – High AFV model availability, no ban on the sale of ICEs, no further incentives offered.
iii. S3 – Medium AFV model availability, ban on the sale of ICEs in 2030, no further incentives offered.
iv. S4 - Medium AFV model availability, no ban on the sale of ICEs, derogation of VAT, VRT, AMT, and no refuelling costs.

S1 in both countries represents the initial question aimed at in this study – what will be the effect of the VRT subsidy retraction. The other question posed by this study, which focused on the cost and effect of further incentivisation of AFV purchasing, are answered in scenarios S2 through S4. The high costs associated with the Danish VRT tax system creates great difficulty in a penetration of AFVs in S2, where the disutility from model availability is largely reduced due to an increase in the number of AFVs available for sale. In the same scenario in Ireland, while the VRT subsidy retraction for BEVs causes a drop off in market sales in 2022, BEVs start to emerge strongly in the market through to 2050. In S3, whereby a ban is placed on the sale of ICEs, and there are half as many AFVs available for sale in 2050 as ICEs, a much faster emergence of AFVs is seen, although the Danish government start to face large drops in revenue from VRT and VAT tax foregone, amounting to €1.1 billion Euros in 2050 alone. Finally in the most costly scenario, S4, where there is no ban on the sale of ICEs, and there is a derogation of VRT, VAT, AMT, and no refuelling costs, there is a fast uptake of AFVs in both Ireland and Denmark, yet this comes at a significant cost to the exchequer, €4.3 billion in Denmark and €2.1 billion in Ireland in 2050.

5. Conclusions and policy recommendations

It is both challenging and expensive to electrify the private transport sector in Ireland and Denmark. To arrive at this conclusion, this study has created a socio-economic consumer choice model which accounts for the costs and disutilities of 15 technologies available to Irish and Danish consumers and linked it with a simulation model of the Danish and Irish private vehicle sector. The purpose of the study is to identify the effect of the currently planned retraction of the vehicle registration tax (VRT) subsidy in Ireland and Denmark, and to assess at what cost and level of effectiveness further incentives may aid in promoting the sale of low carbon vehicles.

In line with these aims, the study finds that retracting the VRT subsidies in accordance with both Irish and Danish national policies will result in a low penetration of alternative fuelled vehicles (AFV) through to 2050. This is especially true in Denmark where there is currently a very generous VRT subsidy, despite the expected decrease in capital costs of battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) (a combined 4.5% market share in Ireland in 2050, up from 0.39% in 2015 and 1.7% in Denmark in 2050, up from 1.6% in 2015).

A high penetration of AFVs in both countries was achieved through placing a ban on the sale of internal combustion engine (ICE) vehicles by 2030, although this comes at a loss to the exchequer in the form of tax foregone as AFVs, in general, are expected to cost less than ICEs in the future and therefore bring in less tax. Placing this ban achieves over an 80% penetration of AFVs by 2050 and comes at an opportunity cost through tax foregone in the range of €162–170 m/year for Ireland and €106–434 m/year for Denmark, dependent on the availability of AFV models for sale. Without regulating the sales of ICEs, Ireland could still achieve a substantial market penetration through a derogation of VAT on AFVs, but this comes at a higher average opportunity cost of €826 m/year. This same market penetration was found to be impossible through single incentives in Denmark, although a combination of VRT and VAT derogation on AFVs provided an 86% stock share by 2050 at an average loss to the exchequer of €3.6b/year.

This challenge and high cost of electrifying private transport is largely due to the number of high disutility costs preventing a large market penetration, but in particular due to the disutility cost associated with the low number of models of BEVs and PHEVs currently available for sale relative to ICEs. Moreover, this is impossible to be overcome through national policy interventions in Ireland or Denmark, as neither country produces automobiles, while their cumulative demand of vehicles is quite low relative to all of Europe, accounting for approximately 2.5% of all European vehicle sales (EEA, 2017). A European wide policy focusing on increasing the number of AFV models available, such as the Zero Emission Vehicle Program adopted by 9 states in the US (CARB, 2009), may be necessary to overcome this barrier whereby manufactures are mandated to sell AFVs.

Further work to this study would include a more thorough analysis of the vehicle market. This study assumed the number of ICEs available for sale did not change from the base year (with the exception of the ban placed on the sale of such vehicles) although in reality the market has a tendency to fluctuate based on a variety of factors. This study is also constrained by the number of behaviour attributes considered within this modelling framework. While this study modelled the intangible costs from model availability, risk related disutility, range anxiety, and refuelling/recharging infrastructure availability, there are a plethora of other preferences which consumers may have when purchasing a vehicle that are outside of the scope of this study.

Competing interests

The authors have no competing interests to declare.

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Appendix A

Table 8.

Table 8
Resulting market share of AFVs and ICEs in 2050 from sensitivity analysis of variance factor, v_a, for the BaU.

Variance factor, v_a	Ireland		Denmark	
	AFV market share	ICE market share	AFV market share	ICE market share
15	6.1%	93.9%	3.3%	96.7%
10	8.4%	91.6%	3.2%	96.8%
20	5.4%	94.6%	3.5%	96.5%

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2018.04.010.

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Glossary

ICE: Internal combustion engines
WTW: Well-to-Wheel
MNL: Multinomial logit
CO_2: Carbon dioxide
BEV: Battery electric vehicle
PHEV: Plug in hybrid electric vehicle
VRT: Vehicle registration tax
VAT: Value Added Tax
AMT: Annual Motor Tax
AFV: Alternative Fuelled Vehicle
SPS: Stated Preference Survey
LCC: Life Cycle Cost
GNP: Gross National Product