Plug-In Hybrid Electric Vehicles

Authored by Kathryn Logan, Joseph Wheatley, and Lisa Ryan

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Executive Summary

Plug-in hybrid electric vehicles (PHEVs) can offer advantages in terms of CO_2 and air pollutant emissions compared with internal combustion engine (ICE) vehicles and can act as a 'transition technology' towards battery electric vehicles (BEVs). In Ireland and many other jurisdictions, subsidies and grants have been introduced to offset the higher upfront cost associated with PHEVs compared with ICE vehicles. These subsidies should be removed once levels of PHEV adoption rise and costs decrease so that there is a self-sustaining market. It is important to optimise the timing of the subsidy removal to ensure a balance between environmental performance, market stability and policy cost-effectiveness.

The aim of this report is to twofold – (i) to carry out a review of current subsidies and grants for PHEVs and plans for their phase out in European countries; (ii) to simulate the PHEV and BEV fleet in Ireland and model the impact of grant phase out timing on the fleet under two techno-economic scenarios.

Policy review

In Ireland there are several grants/subsidies that actively encourage the uptake of PHEVs, including a purchase grant, vehicle registration tax relief, and a charger grant. Our review of policy support for PHEVs in European countries finds that the most common grant is a purchase grant scheme, which in Ireland currently provides a grant of up to €5,000 towards the purchase of a new PHEV (Transport & Environment, 2018). Purchase subsidies in European countries are generally lower than the Irish grant but they often have additional conditions relating to the price, the environmental performance of the PHEV and/or disposal of an older vehicle. For example, in Romania consumers purchasing PHEVs that emit less than 50 gCO_2/km can receive €4,250 to purchase a new vehicle, in addition to €1,250 for scrapping an old vehicle (Autovista Group, 2019). In Sweden, a purchase grant of SEK 10,000 (approximately €980) was available for PHEVs emitting less than 70 gCO_2/km. Many countries offer tax relief for PHEVs also (LeasePlan, 2020). A comprehensive overview of PHEV subsidies in European countries is presented in Appendix 1.

Other non-fiscal incentives offered for PHEVs by local authorities and governments in many countries include free parking, reduction of congestion charges, discounted or no toll charges, and the use of bus lanes for PHEV drivers (DTTS, 2021). In Ireland, PHEVs qualify for a 25% discount on road tolls, up to a threshold of €500 per annum per household for private vehicles and a maximum annual threshold of €1,000 for commercial vehicles (DTTS, 2021). A study in Norway highlighted the value of such schemes to consumers, with 53% of the respondents in the Norwegian EV Association (NEVA) survey from 2016 stating that road tolls were an important incentive, with 14% reporting free parking and 12% reporting access to bus lanes important (Ingeborgrud and Ryghaug, 2019).

Notwithstanding the widespread application of subsidies to PHEVs, there is increasing concern that the emissions savings realised may not be as high as indicated by the emissions ratings. We describe the divergence between 'real world' and 'official' emission levels of PHEVs and the risk this poses for policymaking. Although this is difficult to predict quantitatively under 'real world' conditions, it is crucial for assessing the overall environmental performance of PHEVs.

Official vehicle emissions measurement for the purpose of certification is completed over the Worldwide Harmonized Light Vehicle Test Procedure (WLTP). To estimate the final emissions and fuel consumption of PHEVs, the WLTP uses a utility factor (UF) which determines the share of the test completed by the PHEV using electricity (versus fuel) (Wu et al., 2015). The UF ranges from 0, i.e. an ICEV or hybrid electric vehicle that only drives on a conventional fuel, to 1, i.e. a PHEV and a BEV that only drives electric (Paffumi et al., 2018). Research indicates that there is heterogeneity in the value of UF compared with the values used in the WLTP test among different users. For example, in the Netherlands, Ligterink and Eijk (2014) found that a UF of 24% includes an important sector of business users who do not charge their vehicles regularly. By removing this category, the US increased to 33%. Furthermore, PHEV users tend to drive longer distances and often drive distances further than the electric range of the vehicle. This leads to a greater share of driving distance in ICE mode than in the official emissions rating. This highlights the importance of analysing factors that can influence charging behaviour of PHEV users and thus emissions including driving distances, all-electric range (AER) of the vehicle, and the geographical location of chargers and fuel.

A number of studies have recently highlighted this issue and the resulting lower cost-effectiveness of PHEV policy measures to mitigate CO_2 emissions in transportation. PHEVs are often larger vehicles and the technology is perceived as a way to enable the continuation of the sports utility vehicle (SUV) market. Partly as a result, a number of countries across Europe are planning to phase out subsidies and grants for PHEVs in the coming years. However, a number of these subsidies have been extended in the short term due to COVID-19 in countries such as Spain, Germany and Italy in an attempt to stimulate the economy.

Some EU countries have gone a step further and have now introduced future bans on PHEV sales. For example, Denmark aims to phase out new PHEVs from 2035, five years after their ICEV ban. The UK will ban the sale of PHEVs in 2035, at the same time as banning ICEVs (Igwemezie et al., 2019). In both cases, priority is being given to integrating BEVs and other low emission alternatives in the vehicle fleet.

Phasing out PHEV supports in the EU is primarily due to the increasing recognition that PHEV emissions in the ‘real world’ are often higher than ‘official’ emission levels. The argument that PHEVs are needed as a transition technology on the pathway to electrification of transport has not been demonstrated by Norway, a world leader in BEV integration, but which has had a relatively slow uptake of PHEVs. This slow uptake there is likely due to PHEVs only being made eligible for incentives later than those introduced for BEVs at an earlier date. It is now harder to quantify the timing of future phase out of PHEV grants across Europe in the wake of the pandemic. Post-COVID-19, it is possible that countries will continue subsidies for PHEVs longer than previously considered optimal, in response to the economic crisis and the desire to invest in green technology and support the auto industry.

Impact of PHEV subsidy phase out in Ireland

A micro-simulation model of vehicle purchase decisions by Irish consumers was developed in order to assess the impact of different PHEV and BEV incentive strategies on the vehicle market. The model is based on 2018 survey data on consumer attitudes to EVs and data from the 2021 passenger car market. The impact of BEV and PHEV grant incentive removal on BEV and PHEV uptake and emissions was investigated to 2030 using this model. In particular, we examined the impacts of early removal of PHEV grant supports and the deferral of BEV grant removal to mid-decade. We ran two techno-economic scenarios, one of which leads to high penetration of BEV and PHEVs, or Zero Emission Vehicles (ZEVs) collectively, by 2030 (approximately 39%).

A key finding is that there is a significant penetration of ZEVs even when PHEV incentives are removed early. Maintenance of the current level of grant support for PHEVs is not critical to the electrification transition in Ireland. In both of the techno-economic scenarios modeled, grants boost PHEV uptake in the short-term but do not materially increase ZEV adoption in 2030. Indeed, by the end of the decade, it is projected that BEV technology dominates and PHEV uptake has plateaued (Figure ES1).

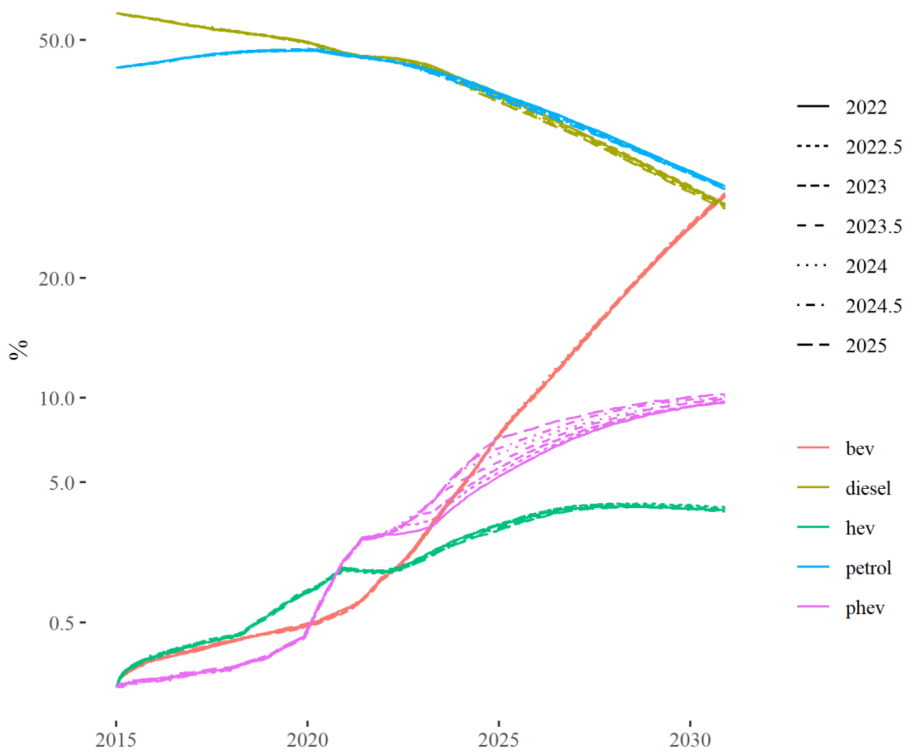

Figure ES1: Fleet composition in Scenario 2 for a range of PHEV grant removal timings.

We find that although PHEV adopters are often higher mileage drivers, grant incentive costs in terms of €/tCO_2 are generally higher than BEV incentives, particularly when PHEV owners are willing to charge their vehicles less than once per day, given by ξ in Table ES1.

grant removal date	€/tCO_2					
	BEV			PHEV		
	$\xi = 0.5$	$\xi = 1$	$\xi = 2$	$\xi = 0.5$	$\xi = 1$	$\xi = 2$
2022.5	-	-	-	1228	590	373
2023	426	452	484	1277	603	380
2023.5	454	481	513	1348	622	391
2024	489	517	550	1413	639	401
2024.5	539	565	597	1468	652	408
2025	589	620	659	1560	674	420
2025.5	651	694	753	-	-	-

Table ES1: Costs in €/tCO_2 of extending BEV and PHEV incentives in Scenario 2

PHEVs do provide electrification options in market segments where there are few affordable BEV options (larger cars and SUVs). However, the new vehicle tax regime introduced in January 2021 would seem to be sufficiently supportive to PHEVs in these segments without maintaining PHEV grant support for an extended period. Figure 7 in the main report shows that PHEVs dominate ZEV uptake in the executive car "E" and large SUV "D-J" segments, although BEVs could begin to compete even in these segments by 2030.

PHEV tail-pipe emissions reductions are not "bankable" in the same way as BEVs because they depend on charging behaviour and daily mileage of adopters. Modelling suggests that encouraging good charging behaviour by PHEV owners, e.g. willingness to charge twice per day, can achieve significant transport emissions reductions. Purchase grants for PHEVs, by themselves, do not incentivise good charging practices and ensure emissions reductions.

In conclusion, emissions from PHEVs are likely to be significantly higher than their type-approval values. This is not another "diesel-gate" but is instead a consequence of driver heterogeneity and sub-optimal charging behaviour. Many countries are looking at ways to taper policy support for PHEVs. This report demonstrates that an orderly removal of PHEV grant incentives does not significantly slow Ireland's mediumterm decarbonisation objectives. On the other hand, improving the charging behaviour of PHEV drivers can yield significant emissions reductions and improve the cost-effectiveness of subsidies for from this technology.

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1.Introduction

Under the Climate Action and Low Carbon Development (Amendment) Bill 2020, Ireland aims to attain *'resilient and climate neutrality by the end of 2050'.* To achieve this, decarbonisation of the transport network will be required as this sector was responsible for 40% of Ireland's energy-related carbon dioxide (CO_2) emissions in 2018 (European Commission, 2020; SEAI, 2018). Manufacturers of internal combustion engine vehicles (ICEVs) have continually improved petrol and diesel engine efficiency and lower emissions per unit of fuel. However, these factors alone will be unable to reduce transport greenhouse gas (GHG) emissions (Faria et al., 2013) as CO_2 emissions from transport have continued to grow in Ireland since the end of the 2012 recession (SEAI, 2018).

Reducing tailpipe emissions from road vehicles has become dominant in EU policy. Under Regulation (EU) 2019/631, new vehicles from 2021 should produce less than 95 gCO_2 km^{-1}, which corresponds to fuel consumption of 4.1 l/100 km of petrol or 3.6 l/100 km of diesel (European Commission, 2018). To meet these targets, plug-in hybrid electric vehicles (PHEVs) have been introduced as they consume less energy than ICEVs. PHEVs have the ability to act as a 'transition technology' towards battery electric vehicles (BEVs). For example, in the UK, the Department of Transport predicts that PHEVs will replace ICEVs, before a full transition to BEVs by 2050 due to factors such as range anxiety, lack of charging infrastructure and time required for charging (Hu et al., 2011; Küfeoğlu et al., 2020).

PHEVs in Ireland have been made competitive by policy incentives that support the electrification and infrastructure processes. However in 2019, PHEVs sales only made up about 1.1% of new vehicle registrations (Contestabile et al., 2017; ICCT, 2019). As a higher level of PHEV adoption occurs, policy support measures are withdrawn, and the impact will directly affect the user itself. In Ireland, the Sustainable Energy Authority of Ireland (SEAI) has introduced several subsidies and grants to make PHEVs a more favourable transport type in comparison to ICEVs. Whether or not this transition to PHEVs will be successful will be determined by whether it will be able to sustain itself (Contestabile et al., 2017).

The objective of this paper is to analyse whether Ireland should continue to fund subsidies and grants for PHEV integration and to make policy recommendations in line with other EU countries. **Section 2** describes the factors that determine the real-world emissions of a PHEV. This includes the differences between 'real world' and 'official' test PHEV emissions and why we need to analyse PHEV emissions, a discussion of the utility factor (UF), and the factors that influence a PHEVs UF and how this can impact the divergence between 'real world' and 'official' emissions. **Section 3** describes current EU policies introduced in Ireland and how these compare with the rest of the EU, inter-policy interactions between PHEVs and BEVs and how they influence uptake and why countries are considering phasing out PHEV incentives. This section also describes how COVID-19 has influenced the phasing out of incentives. **Section 4 describes** a micro-simulation model integrating two techno-economic scenarios and a range of BEV and PHEV subsidies/grant removal scenarios. Results are described in **Section 5.** Appendix 1 provides an overview of the PHEV subsidies in place across European countries. Appendix 2 provides further details of the PHEV charging/emissions model. Appendix 3 describes some aspects of the 2021 new passenger car fleet. Appendix 4 compares the microsimulation model results to the Bloomberg New Energy Finance EV Outlook projections.

2. Factors in PHEV emissions measurement and estimation

- ### 2.1 'Real world' and 'official' PHEV emissions

PHEV emissions are difficult to predict quantitatively under 'real world' conditions but are crucial for assessing the overall environmental performance of PHEVs (Ehrenberger et al., 2020)[1]. PHEVs can be categorised into two modes (Karabasoglu and Michalek, 2013). The first is the charge-depleting (CD) mode, where the state of charge (SOC) remains above the target SOC through a pre-set threshold value (in UN-ECE R101[2], this is indicated as "Condition A") (Amjad et al., 2010; M. Sabri et al., 2016; Schuitema et al., 2013; Somayajula et al., 2009). This allows PHEVs to receive all or some of its net propulsion energy from the battery pack (Karabasoglu and

[1] Emissions are produced in a PHEV upon the re-start of the internal combustion engine vehicles (ICEVs).

[2] Regulation No 101 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of passenger cars powered by an internal combustion engine only, or powered by a hybrid electric power train with regard to the measurement of the emission of carbon dioxide and fuel consumption and/or the measurement of electric energy consumption and electric range, and of categories M 1 and N 1 vehicles powered by an electric power train only with regard to the measurement of electric energy consumption and electric range.

Michalek, 2013). Once the battery has depleted to the target SOC, the vehicle then switches to the charge-sustaining (CS) mode where petrol is used to provide the propulsion energy and the electric system is only used as momentary storage to improve the fuel economy (Karabasoglu and Michalek, 2013). Therefore, a PHEV does not cause consumers to suffer from ‘range anxiety’ as the vehicle has a ‘back up system’ using conventional fuel (Wu et al., 2015). Alternatively, some PHEVs operate on a CD mode using only electrical energy, referred to as an all-electric range (AER) which enables short trips without the use of petrol, but with electric motors and battery designs that maximise the vehicles power demands (in UN-ECE R101, this is indicated as “Condition B”) (Karabasoglu and Michalek, 2013). As a result, PHEVs have captured considerable interest from researchers given their enhanced approach to the issues of fuel economy and tailpipe emissions (Chen et al., 2020; M. Sabri et al., 2016; Plötz et al., 2018). Furthermore, numerous studies have demonstrated that through dependence on the power generation, the adoption of PHEVs provides significant, economic, environmental and health benefits (Dijk et al., 2013; Doucette and McCulloch, 2011; Egbue and Long, 2012; Huang et al., 2012; Kudoh et al., 2001; Lebeau et al., 2012; Requia et al., 2017).

Recent studies have demonstrated an increased divergence, or ‘gap’ between ‘real world’ and ‘official’ energy use and air pollutant emissions of road vehicles (Ligterink and Eijk, 2014a; Tietge et al., 2017). For example, on tests where a car was started with an empty battery, CO_2 emissions from a Volvo XC60 and a Mitsubishi Outlander surged up to 184 gkm^{-1} and 164 gkm^{-1} respectively, the equivalent of three to four times their official values (Transport & Environment, 2020). This likely divergence between ‘emissions is often linked to differences in the driving cycle (i.e. speed, acceleration, and altitude profile), vehicle conditions (i.e. test mass, driving resistances, start conditions, etc.) and the optimisations of the vehicle control strategies for the type approval test (if applied) compared with ‘real world’ driving (Weller et al., 2019). There has been increasing evidence that fuel consumption improvements originate from test-orientated optimisations and practices as opposed to operating fuel saving technologies (Fontaras et al., 2017; Fontaras and Dilara, 2012). Therefore, the aim of this study is to address why there are differences within these emission types and whether they are a good ‘transition technology’ towards low carbon transport in Ireland.

2.1.1 European emission standards and test cycles for PHEVs

To estimate the divergence between ‘real world’ and ‘official’ emissions from PHEVs, emissions and fuel economy values of passenger vehicles in Europe were measured using standard test-cycles such as the New European Driving Cycle (NEDC) procedure (Regulation (EU) 715/2007) (Plötz et al., 2018). All vehicles registered within the EU had to comply with these standards. Although the NEDC produced reproducible figures, it generally underestimated the ‘real world’ fuel consumption and CO_2 emission values (Tietge et al., 2017). Therefore, in 2017, the NEDC was updated with new mandatory CO_2 standards which will see passenger car emissions reduced by 15% by 2025 and 37.5% by 2030 relative to 2021 standards, called the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) (Regulation ((EU) 2018/1832), mandatory from 2018 onwards (Ehrenberger et al., 2020; ICCT, 2019).

For a PHEV to successfully pass the WLTP, and to ensure a fair comparison between vehicle types, PHEVs are tested under the CD mode and have to perform the necessary WLTP cycle until the battery is totally depleted (SOC = 0.35) (Serrano et al., 2021). Under homologation conditions, the PHEV starts with the battery fully charged (i.e. SOC = 1.0) and is reconnected to a charger after testing. The energy necessary to recharge the battery is measured and added in the final vehicle homologation (Serrano et al., 2021). The CS always represents one WLTC with the battery charge oscillating ~4% of the necessary energy to complete the driving cycle (Serrano et al., 2021). The parametric implementation of the limits for the SOC in CS mode is due to the difference of energy that PHEV carry in their batteries.

To improve the reliability of the results between ‘real world’ and ‘official’ PHEV emissions, the WLTP made three key improvements to the former NEDC to both the test cycle and test conditions, allowing results to be closer to ‘real world’ driving conditions and provide insight into more realistic fuel consumption values (Weller et al., 2019). Firstly, improvements to ensure more representative results from average driving behaviour, more dynamic, and incorporate a higher maximum speed. This more realistic driving profile should allow the AER and fuel consumption of a PHEV within the WLTP to be closer to what is observed by vehicle owners under a ‘real life’ scenario. The electric range is expected to be reduced by ~25% with respect to the NEDC range. Secondly, the Worldwide harmonized Light vehicles Test Cycles (WLTC), are framework dynamometer tests for the determination of emissions and fuel consumption from light-duty vehicles, part of the WLTP, were subdivided into four phases. These can be regarded as typical driving for an urban, rural, 100-km/h limit, and 130-km/h limit motorways. Finally, WLTP includes a variable weighting factor that more accurately describes the ratio of driving in CD and CS mode as a function of the electric range based on driving data. With these changes in the WLTP, it is hoped that the divergence in emission levels for PHEVs will be reduced.

- **2.2 Influence of the utility factor**

For the final emissions and fuel energy consumption, the WLTP uses the utility factor (UF). This is the distribution a PHEV will travel using the AER and the internal combustion engine, which combines the on-road energy consumption with the emissions from pollutants (Arslan and Karasan, 2013; He et al., 2016; Ke et al., 2017). This does not take into account the electricity generation from the PHEV.

The UF can range from 0, i.e. an ICEV or hybrid electric vehicle that only drives on a conventional fuel to 1 i.e. a PHEV and a BEV that only drives electric (Paffumi et al., 2018). Therefore, the UF of a PHEV can act as a measure of how environmentally friendly a PHEV is because the UF directly reflects the benefits of driving a PHEV in terms of replacing the internal combustion engine with electricity (Wu et al., 2015). For example, the regional heterogeneity of the UF in the USA ranges from below 0.6 in the Midwest and the Northeast to above 0.8 in Alaska (MacPherson et al., 2012).
For example, in the Netherlands, Ligterink and Eijk (2014b) found that a UF of 24% includes an important sector of business users who do not charge their vehicles regularly. By removing this category, the US increased to 33%. Furthermore, Goebel and Plötz (2019) highlighted that a PHEV with an AER of 42 miles was found to have a UF of 64% if fully charged once a day compared to 86% if fully charged before every trip. This therefore highlights the variation within the UF which is important to consider for future analysis because the share of AER, alongside the efficiency of the ICEV, determines the level of CO_2 emissions produced.

For policymakers, a curve of UF against the battery capacity is often used to understand the efficiency of PHEVs in terms of substituting petrol within their operation (See **Figure 1**) (Wu et al., 2015). The UF contains assumptions about how the consumers uses their PHEVs, for example, if the PHEV is only charged once per day, vehicles are driven in the same patterns as the national average vehicles and that the energy consumption mode changes are best characterised by a CD range (Paffumi et al., 2018). This is not always the case and emissions levels will vary widely from one user to another, resulting in divergences between ‘real world’ and ‘official’ emission levels. For example, in the USA, a PHEV, using the extending strategy, has a CD range of 20km and when tested to determine the petrol fuel consumption from 100% SOC using the USA’s Federal Test Procedure (FTP) 75 test (a test designed by the US Environmental Protection Agency), the PHEV will complete the test entirely in the CD mode (Bradley and Frank, 2009; Bradley and Quinn, 2010). This is because the FTP75 has a test distance of 17.8km, less than the CD range of the vehicle therefore ‘cheating’ the test (Bradley and Frank, 2009; Bradley and Quinn, 2010).

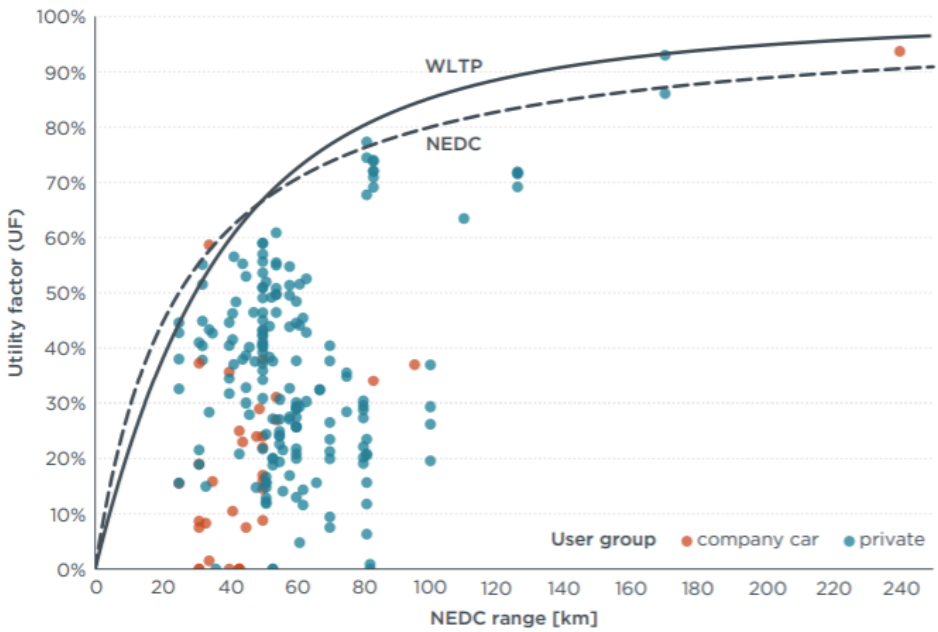

Figure 1: ICCT 2020 empirical utility factors compared to type-approval utility factor curve (Source: Plötz et al,. 2020).

○ 2.3 Factors influencing PHEV emissions emission levels

The differences between ‘real world’ and ‘official’ emissions from PHEVs are expected to be even higher than the analysis from the WLTP due to the differences within the operating shares of the two different components (i.e. the internal combustion engine and the electric battery) required to fuel PHEVs (Plötz et al., 2018). In this section, we discuss some of the factors that are likely to influence the emission levels.

Within a policy making and future regulations context, policy should be based on ‘real world’ consumption measurements from PHEV and geographical location of chargers because fuel prices can directly impact driving and charging behaviour of users, which in turn has an impact on the GHG emissions reduction potential of PHEVs (Boston and Werthman, 2016; Plötz et al., 2018; Tal et al., 2014). For example, Smart et al., (2014) highlighted that for a large set of privately owned Chevrolet Volt cars, drivers achieved higher percentages of distance travelled in BEV mode because of fewer long-distance travel days than drivers in the national travel survey referenced in the USA’s WLTP equivalent (Society of Automotive Engineers protocol J2841) because they charged more frequently than once a day (~1.4 charges per day). However, Plötz et al., (2020) claimed that PHEVs users charge their vehicle less frequently at an average of three out of four driving days which reduces the share of kilometres driven on electricity. Therefore classifying vehicle users into categories such as part-time workers, commuters and professional drivers should be considered as this has the potential to influence vehicle use and emissions production (Bubeck et al., 2016). By recognising the importance of travel patterns, emission levels should be considered as this has the potential to fluctuate as actual PHEV emissions are predominantly determined by driving patterns and charging behaviours (Hao et al., 2020; Tal et al., 2014).

Several factors can influence the UF of a PHEV which can lead to discrepancies in emission levels, for example, the UFs can be reduced if only off-peak charging is available in comparison to when charging is available at all times (Axsen et al., 2011; Sun et al., 2018). Furthermore, the UF of a ride-sourced PHEVs is almost half that of a private PHEV largely due to ‘deadheading’, i.e., empty ride-sourced trips with drivers that use smartphone apps to connect with passengers to passenger pick-up locations (ITF, 2020). Additionally, UFs can be influenced by extreme ambient temperatures, which can reduce the fuel economy of PHEV (Wu et al., 2015), with higher energy consumption reducing the AER of the PHEV which leads to a lower UF, and with climate change leading to more heat extremes, this issue could become more apparent (Wolfram and Hertwich, 2021).

Özdemir and Hartmann (2012) analysed the energy consumption of PHEVs, costs and GHG abatement costs depending on the AER of the average driver within a German market. Their results indicated that the optimum electric driving range for minimum costs and GHG abatement costs was between 12-32 km and 16-23 km respectively. Their results also highlighted that the main factors influencing the results were the annual mileage and the oil prices (Redelbach et al., 2014). Recent tests applying the WLTP with EURO 6 compliant PHEVs, similar to Özdemir and Hartmann (2012) study, have highlighted that these vehicles can emit similar or even higher levels of emissions than ICEVs (Ehrenberger et al., 2020; Suarez-Bertoa et al., 2019). However, there remains variation in energy consumption and potential tailpipe emissions, which need to reflect in the evaluation of potential environmental benefits of PHEVs due to the different vehicle types.

The construction phases of a PHEV battery produce lower CO_2e emissions than a BEV by ~2 tCO_2e on average. However, as PHEVs have internal combustion engines, this leads to additional emissions of ~0.6 tCO_2e per vehicle (Plötz et al., 2017). Taking all this into consideration, the overall CO_2e emissions are ~1.4 tons higher for a BEV than for a PHEV (Plötz et al., 2017). Technological advancements in battery production, in combination with improved electricity mix, might reduce these emissions in the future.

This divergence in emission levels has resulted in many researchers conducting life cycle analysis (LCA) studies of the total emissions produced for different road transport types. An LCA model is a methodological framework used for estimating and assessing the environmental impacts attributable to the life cycle from the direct and indirect CO_2 emissions related to the construction, operation and scrappage throughout the entire process (Rebitzer et al., 2004). An LCA is particularly useful for transport due to the interrelated effects that can be influenced by vehicle production and use. However, due to the lack of long term measurements and monitoring, only a few LCAs have the ability to provide an overall picture of emissions as a number of estimations are required to project the emission levels for vehicles (Egede et al., 2015). This can include factors such as the design of the vehicle, which has the potential to greatly influence the environmental impact of other stages within the life cycle. For example, if the design of a vehicle is determined by the fuel consumption and emissions per kilometre driven when the vehicle is in use, then this may not influence the GHG cost of construction or the reusability of materials within the end-of-life phase (Rebitzer et al., 2004). Therefore further research may need to be done through an LCA of PHEVs and an ICEV to compare and fully understand the divergence in emission levels from the construction to the scrappage of these vehicle types.

3. Current policy surrounding PHEVs

Incentives for purchasing PHEVs vary between countries. A combination of tax rebates, subsidies and sales tax exemptions have resulted in a significant increase in the penetration rate of PHEV technology in recent years (Al-Alawi and Bradley, 2013; van der Steen et al., 2015; Yang and Timmermans, 2020).

Ireland introduced several grant and taxation schemes to encourage the uptake of PHEVs (as seen in **Table 1**). The schemes have encouraged low emission private transport; the higher number of PHEV models compared with BEVs act as a transitional option to electric mobility for Irish customers (O’Neill et al., 2019). PHEVs emerged into the Irish market in 2014, accounting for 35 of the 257 vehicle models available on the market, however Ireland has remained a BEV-orientated market (O’Neill et al., 2019).

In January 2021, despite a decline in market share, diesel remained the most popular engine type with a 35.9% market share, followed by petrol vehicles (34.7% market share) (SIMI, 2021). Hybrid vehicles have increased significantly (19.1% market share in 2021) since January 2020, with a 4.2% market share in PHEVs, slightly higher than BEVs at 3.9% market share (SIMI, 2021). The monetary incentive for PHEVs is less than that of BEVs in Ireland (**Table 1**) and this has historically been reflected in the sales numbers – 2491 PHEVs and 4013 BEVs sold in 2020. PHEV sales now appear to be rising, with PHEV sales (1098) overtaking BEV sales (980) for the first time in

January 2021. The sale of PHEVs in January 2021 represented an increase of more than 100% compared with January 2020, in contrast to a fall of all passenger car sales of 17% compared with the same period in 2020.

Table 1: Current list of plug-in hybrid electric vehicle grants and schemes in Ireland (Source: DTTS, 2021).

Grant/Scheme	Description
Purchase Grant Scheme	A grant of up to €5,000 towards the purchase of a new PHEV which is applied directly through the relevant motor dealership.
eSPSV20 Purchase Grant	A grant of up to €5,000 towards the purchase of a PHEV for vehicles in the taxi/hackney/limousine sector. If the PHEV is wheelchair accessible, this increases up to €7,500.
Domestic Charger Grant	A grant of up to €600 towards the installation of a domestic charging point for new or second-hand PHEVs.
Accelerated Capital Allowance (ACA)	PHEVs and their associated recharging infrastructure qualify under the ACA scheme which allows businesses to identify and buy the most energy efficient equipment (including electric charging infrastructure) and write down the cost of such equipment in the year of purchase rather than over the traditional eight years.
Vehicle Registration Tax (VRT) Relief	New PHEVs qualified for VRT relief of up to €2,500, providing a maximum combined subsidy (grant + VRT relief) of €7,500, provided the vehicle emits less than 65 gCO_2km^{-1} (until end of 2020).
Motor Tax	PHEVs are taxed based on emissions and fall within one of the lowest tag bands, typically at ~€170 per annum if emissions are less than 80g/km (NEDC CO_2) (January 2021).
Toll Incentive Scheme	PHEVs qualify for 25% toll reductions of up to €500 per annual household threshold for private vehicles and a maximum annual threshold of €1,000 for commercial vehicles. A higher rate of 50% for PHEVs during off-peak travel on the M50. This incentive is to remain in place until 2022 or a threshold of 50,000 registrations have been reached.
Company Tax Benefits	A tax incentive for companies paying corporation tax is in place in the form of Accelerated Capital Allowances for Energy Efficient Equipment. Since 2008, this scheme has been allowing companies to write off 100% of the purchase value of qualifying energy efficient equipment against their profit in the year of purchase. The scheme supports the purchase of PHEVs and the associated charging equipment.

3.1 Purchase grants for PHEVs in EU Member States

To encourage PHEV uptake, Ireland introduced a purchase grant of up to €5,000 (Transport & Environment, 2018). Most EU countries have introduced purchase incentives for PHEV with different variations (EEA, 2016). **Appendix 1** provides a comprehensive overview of incentives in EU member states for PHEVs and BEVs.

In terms of cost of purchase grants for PHEVs, countries such as Croatia and Slovenia have introduced similar monetary values as Ireland at €4,600 (if funds are available) and €4,500 respectively. Alternatively, PHEVs are exempt from purchase tax in Poland until the beginning of 2021.

Some EU countries have set both a purchase grant and a maximum level of emissions the vehicle is allowed to emit. For example, under the renewable scheme (RABLA) in Romania, consumers purchasing PHEVs that emit less than 50 gCO_2km^{-1}, could receive €4,250 to purchase a new vehicle, in addition to €1,250 for scrapping an old vehicle. This scheme was successful and saw funding double in 2019 after the initial RON 15 million (€3.2 million) funding was 'fully used in about three months after its launch' (Autovista Group, 2019). Luxembourg introduced a €2,500 incentive as part of the consumer's tax return for PHEVs emitting less than 50 gCO_2km^{-1}. Sweden introduced a higher purchase grant of SEK 10,000 for PHEVs emitting less than 70 gCO_2km^{-1}; however this grant was phased out from December 2020 (LeasePlan, 2020). France has introduced a stimulus package in response to COVID-19 which includes a subsidy of up to €2,000, but consumers can apply for a maximum scrappage aid of up to €5,000 for a PHEV with an AER of 50km, up until mid-2021 (ICCT, 2020).

Similarly, Spain has introduced two aid plans in response to COVID-19. The first plan, called the MOVES II Program, adopted in June 2020, provides consumers with a purchase grant of €4,000 for a PHEV with a minimum AER of 90km and a scrappage incentive of €5,500 (ICCT, 2020). Smaller range PHEVs with an AER of between 30 and 89km can receive up to €1,900 without and €2,600 with scrappage (ICCT, 2020). The second aid plan, called the RENOVE 2020 Program, introduced in July 2020, allows PHEV consumers a maximum financial aid of €4,100. PHEVs emitting up to

120 gCO_2km^{-1} on the NEDC (gasoline at least Euro 4 and diesel at least Euro 6) can receive a maximum bonus of €2,100 (ICCT, 2020).

Italy has introduced a COVID-19 recovery plan which allows consumers to purchase PHEVs with a grant of €3,500 without scrappage (previously €1,500) and €6,500 with scrappage (previously €2,500) (ICCT, 2020). In addition, consumers of a Euro 6 ICEV with emission levels between 61 and 110 gCO_2km^{-1} (as measured in the NEDC) receive a bonus of €1,750. If an older car is scrapped, the amount doubles to €3,500 (ICCT, 2020).

To ensure that purchase grants are used responsibly, some EU countries have introduced purchase grants with a cap on the maximum list price of a vehicle. For example, the UK introduced a grant of £2,500 for PHEVs purchases, with a maximum list price of up to £60,000 (Hardman et al., 2017). Similarly, the German Government doubled the incentives for PHEVs as part of its COVID-19 recovery package to €4,500 (ICCT, 2020). This financial aid is complemented by incentives offered by the car industry of €2,250 up to a maximum of €6,750 (previously €4,500) (ICCT, 2020). The German recovery package does not include any subsidies for the purchase of new ICEVs. Prior to this, the German Government had applied an 'innovation bonus' which increased the environmental bonus for new and used PHEVs until December 2021. From June 2020, PHEVs with a net list price of less than €40,000 are eligible for a grant of €6,750 and if the vehicle cost is between €40,000 and €65,000 they are eligible for a grant of €5,625.

Austria introduced one of the stricter purchase grant policies with a low subsidy of up to €1,500 for new PHEVs, with an AER of 50km, and a gross list price of less than €60,000. However from 2019, PHEVs with diesel were no longer eligible for this subsidy (Randall, 2019).

Helveston et al., (2015) modelled consumer preferences for subsidies for ICEVs and PHEV technologies in China and the U.S. Their results indicated that if both countries wanted to achieve a 50% share of PHEVs in comparison to petrol ICEVs (indicating no net preference for one over the other in the population), low AER PHEVs would require a subsidy of ~$9000 and ~$18,000 or more in the USA and China respectively

(Helveston et al., 2015). A larger AER PHEV would require subsidies exceeding ~$20,000 in both countries to achieve a 50% share. Under current subsidies, a low AER PHEVs could achieve between 41 and 44% share in the U.S. and between 32 and 36% share in China in comparison to a petrol ICEV (Helveston et al., 2015). Therefore indicating that these subsidies could actively encourage a transition towards PHEVs. However, larger AER PHEVs could achieve only between 25 and 33% share in the USA and between 26 and 35% share in China in comparison to a petrol ICEV (Helveston et al., 2015).

3.2 Vehicle registration tax

Until December 2020, Irish consumers purchasing new PHEVs qualified for vehicle registration tax (VRT) relief of up to €2,500, providing a maximum combined subsidy (grant + VRT relief) of €7,500 if the CO_2 emissions were less than 65 gkm^{-1} (Revenue, 2021). VRT relief for PHEVs expired on the 31st of December 2020 and will not be renewed. Instead, the VRT on category A vehicles (which includes passenger vehicles and SUVs) is calculated using the CO_2 emissions under the WLTP measuring system. This implementation sees an increase in the number of VRT bands to 20, with a wider gap between the lowest VRT rates (from 7% to 37%, previously 14% to 36%) (VRT Ireland, 2021).

Lithuania introduced exemptions to registration tax if the vehicle emits less than 130 gCO_2km^{-1}. Within the EU, Denmark is the only other country that has introduced a purchasing or registration tax relief, which allows PHEV consumers to only pay 20% of the registration tax up to 2020. After that, PHEVs start at 45% provided they emit less than 50 gCO_2km^{-1} and this is set to increase by 5% per year to 65% in 2025, and by 3% each year to 80% by 2030. A further increase of 4% will then occur reaching 100% by 2035 (Autovista Group, 2020).

In 2018, Mulholland et al. compared Irish policy with Denmark as they had begun to remove their subsidies for BEVs and PHEVs by 2020. The initial reduction of the VRT subsidy for BEVs and PHEVs in 2016 in Denmark saw a decrease in combined BEV and PHEV sales of 42% relative to the previous years. Mulholland et al. (2018) highlighted that there would be a decrease in the sale of PHEVs in Ireland if the VRT relief was removed leading to lower penetration of alternatively fuelled vehicles through to 2050. Under a 'business as usual' study, with no variation in the number of models available for sale, the market share of BEVs in Ireland would be expected to rise from 0.39% in the base year to 1.2% in 2021. PHEV sales would then fall to 0.3% once the VRT subsidy is removed in 2022. This market share then rises steadily to 4.5% by 2050. This change is expected to be driven by the assumed reductions in the cost of BEVs and cost increases in ICEVs.

3.3 Other subsidies and incentives

Other non-fiscal incentive schemes exist in some European countries. In Norway, PHEV and BEV drivers were exempted from toll charges. Mersky et al. (2016), in their analysis of toll exceptions and the right to use bus designated lanes, did not find these to have had a statistically significant impact on the sale of BEVs in Norway. However, their results could be influenced by neighbouring major cities not having these incentives. Conflictingly, Ingeborgrud and Ryghaug (2019) study highlighted 53% of the respondents in the Norwegian EV Association (NEVA) survey from 2016 stated that road tolls were an important incentive, with 14% reporting free parking and 12% reporting access to bus lanes important.

In addition, some EU countries introduced VAT benefits when purchasing PHEVs. For example, Portugal has a VAT reduction for PHEVs if the vehicle value is less than €50,000. Similarly, in the Canary Islands in Spain, PHEVs are VAT exempt if they emit less than 110 gCO_2km^{-1}. In addition, Germany temporarily lowered their VAT from 19 to 16% for PHEVs and BEVs between 1 July - 30 December 2020.

In 2017, Greece abolished the luxury tax for low emitting PHEVs, which was an additional tax for passenger cars based on the wholesale price of a vehicle. The tax was specifically aimed at vehicles with a price over € 20,000 (European Commission, 2019). These have since been replaced with a 15% cashback for PHEVs that emit ≤50 gCO_2km^{-1} of up to €8,000, plus extra €2,500 if an old taxi is scrapped. In addition, consumers received 15% cashback for vans (up to €4,000 for PHEVs), plus €1,000 for scrapping.

3.4 Phase-out of PHEV subsidies/grants

Vergis and Chen (2015) analysed the financial benefits and state-specific property impact on the market shares of BEVs and PHEVs through an analysis of a stepwise linear regression on US state-level data. Their results concluded that, apart from consumer, geographic and energy market attributes, the availability of charging infrastructure directly impacts the levels of BEV adoption, whilst for PHEVs, monetary incentives and model availability are the most decisive factors (Münzel et al., 2019). Therefore, incentives remain a key factor on whether there will be increased uptake of PHEVs.

However, a number of subsidies and grants for PHEVs across Europe (mentioned in **Section 3.1**) are planned to be phased out in the coming years. This is primarily due to the fact that there is increasing recognition that the level of PHEV emissions in the 'real world' are often higher than 'official' emission levels. This has been taken into account in some EU countries which have now introduced future bans on PHEV sales. For example, Denmark aims to phase out new PHEVs from 2035, five years after their ICEV ban. The UK will ban the sale of PHEVs in 2035, at the same time as banning ICEVs (Igwemezie et al., 2019). In both cases, priority is being given to integrating BEVs and other low emission alternatives in the vehicle fleet.

PHEVs are not always the most practical and cost-effective transport type to achieve the intended emission reduction targets. This could be considered problematic as the type of transport initially deployed i.e. BEVs or PHEVs, will influence the future behaviour and preferences of adopters (Contestabile et al., 2017). This can, in turn, contribute to pushing specific technology and infrastructure down a certain path and influence consumer adoption of new vehicle models and the development of policy and regulation in a process that is often described as co-evolution (Contestabile et al., 2017; Dijk and Yarime, 2010; Geels, 2012).

Most European countries have begun to increase their support for BEVs relative to PHEVs (Contestabile et al., 2017). Seixas et al., (2015) highlighted that BEVs will become cost effective for European consumers by 2030 if costs decrease from their current expectation by 30% regardless of the mitigation cap, and by 10% by 2040 if a more stringent mitigation cap is considered. Their study demonstrated that this cost decrease of BEVs would hamper the cost effectiveness of PHEVs, therefore careful consideration should be taken into account when designing policies to promote electric mobility and how financial purchase incentives play a role when integrating BEVs. Taking that into consideration, Santos and Davies (2020) analysed the penetration of BEVs in five EU countries and highlighted that respondents had concerns regarding the short-term characteristics of most government purchase subsidies which are typically only in place for a few years (Wang et al., 2017). Therefore longer time frames for subsidies would encourage this transition towards BEVs, especially if PHEV subsidies are removed.

To initially increase PHEV and BEV sales, VAT exemption was a popular incentive in Iceland. However, from July 2020, the VAT exemption for PHEVs was decreased from 960,000 ISK to 480,000 ISK per vehicle (Lin and Sovacool, 2020). Alternatively the VAT exemption for BEVs has increased from 1.440.000 ISK to 1.560.000 ISK per vehicle (Lin and Sovacool, 2020). In addition, free parking in the city centre of Reykjavik and Akureyri was reduced to two hours. Free parking available within the city centre, this has resulted in PHEVs and BEVs competing directly against each other for resources including charging facilities and has led to the market share of PHEVs almost four times higher than BEVs (Lin and Sovacool, 2020).

Comparably, Norway has had a relatively slow uptake of PHEVs, although remains a world leader in BEV integration. This slow uptake is likely due to PHEVs only being made eligible for incentives late that had already been introduced for BEVs at an earlier date (Broadbent et al., 2017). For example, PHEVs are eligible for between a 10 to 15% reduction of the weight-based part of registration tax, this remains a fraction of the total tax, with BEVs exempt from VAT and registration tax, highlighting a strong fiscal support for BEVs and not for PHEVs (Lévay et al., 2017). Therefore, the relative sale of BEVs in Norway reflects the pattern of these incentives. Lévay et al., (2017) stated that in 2017 BEVs had the highest relative registration numbers whereas the lowest three are the Toyota Prius PHEV (0.7%), the Volvo V60 PHEV (4.2%), and the Mitsubishi Outlander PHEV (49.7%). The Mitsubishi Outlander PHEV sells well as its net price is similar to the ICEV version and the TCO is similar. Alternatively, the Toyota Prius PHEV and the Volvo V60 PHEV cost between €10,000 and €20,000 more than the ICEV equivalents, with fuel costs and CO_2 costs not offsetting the net price difference and are therefore not considered competitive (Lévay et al., 2017). However, Norway also plans to downsize their BEV incentives in the coming years, which is expected to have little, if any, impact on consumers purchasing BEVs due to a well-developed market (Figenbaum, 2017).

The type of subsidy and when these subsidies are implemented should be considered for PHEV integration, as this has the ability to determine how successful their implementation could be. For example, similar incentives were introduced for PHEVs and BEVs in the Netherlands, with the market share of PHEVs dominant up until 2016. However, the Dutch Government realised that consumers were purchasing PHEVs to gain the incentive benefits with the purchase but barely using the electric motor. This has led to the Netherlands to introduce significant purchase subsidies for BEVs in 2021, with the number of BEVs expected to multiply (Business Wire, 2021).

Furthermore, subsidies and grants may not have been fully utilised or introduced with the consumer in mind, making the transition from ICEVs to PHEVs unsuccessful. The Netherlands issued a change to the company car tax for PHEVs in 2016 which saw a substantial decrease in PHEV purchases, partly due to company cars representing 40% of new vehicle sales. In 2017, the company car tax for PHEVs was decreased to 22%, however this did not cause an increase in sales as this value was too similar to the standard rate of 25% (Santos and Davies, 2020). Therefore taxes still need to remain competitive with ICEVs for uptake to increase.

This interaction between PHEV and BEV incentives may hinder development towards a low carbon transition. Sierzchula et al., (2014) emphasised that financial policy instruments are strongly and positively correlated with national BEV market shares through a study from 30 countries. This was similarly analysed through Ozaki and Sevastyanova (2011), with their research focusing on consumer incentives to purchase a Prius, highlighting that perceived financial benefits strongly affected the decision to purchase a hybrid vehicle (including lower tax, congestion charge exception and fuel economy). However, there were exceptions, including in Belgium and Denmark, which had high levels of financial incentive but low rates of adoption (Sierzchula et al., 2014). Conversely, Switzerland and Sweden saw the opposite with lower consumer subsidies and higher BEV uptake. Ozaki and Sevastyanova (2011) attribute this disproportional adoption rate to social norms and pressure, practical compatibility, self-expression and positive attitudes towards technology.

As PHEVs are integrated into the transport network, it has been argued that PHEV manufactures should increase the AER of PHEVs as this would allow individuals to travel on lower emission transport. However, PHEV drivers are typically high mileage drivers, therefore are often not driving in the AER. By increasing the AER of the PHEV by 10 miles, Shiau et al., (2009) claimed that this would result in an additional ~95 kg of vehicle weight. This additional weight would reduce both the CD and CS mode efficiencies by 0.10 mile/kWh and 0.68 mile/gal, respectively (Shiau et al., 2009). These efficiency reductions could cause an increase in vehicle operating costs of between $0.40 and $0.80 per 1000 miles in CD and CS mode, respectively, and an increase in operation-associated GHG emissions of between 3.0 to 3.2 kg CO_2-eq per 1,000 miles in CD and CS mode, respectively (Shiau et al., 2009). This therefore demonstrates that simply increasing the AER, the benefits may be minimal, and consumers should consider a BEV if they will regularly travel less than the AER of a PHEV on an average trip.

Overall, a number of the subsidies and grants for PHEVs have begun to be phased out across Europe. However, some of these are on hold due to the COVID-19 pandemic. With the differences between ‘real world’ and ‘official’ emissions, most EU countries are transitioning towards BEVs and ensuring incentives are in place for these vehicles. This is also due to PHEVs and BEVs competing against one another and hindering the development towards a low carbon transition through competition between one another.

4. Microsimulation of PHEV & BEV incentives

The extreme challenge of climate change mitigation is pushing transport policy into uncharted territory. Unfamiliar new technologies and associated policy measures mean that the evidence base available from historical data is limited (Axsen et al,. 2020). Simulation modeling can be a useful tool in this situation. This section of the report describes micro-simulations of ZEV uptake and, in particular, the impacts of retaining grant support for a greater or lesser time. The same model can also be used to examine a variety of other policy scenarios. The results are described in **Section 5**.

4.1 Scenarios modeled

Vehicle adoption is modeled using two background techno-economic scenarios:

- Scenario 1: pump prices for petrol increase linearly reaching €2/l by the end of 2030. Lithium-ion battery pack prices fall below 100€/kWh by 2027.
- Scenario 2: pump prices for petrol increase linearly reaching €2.40/l by the end of 2030. Lithium-ion battery pack prices fall below 100€/kWh by 2026.

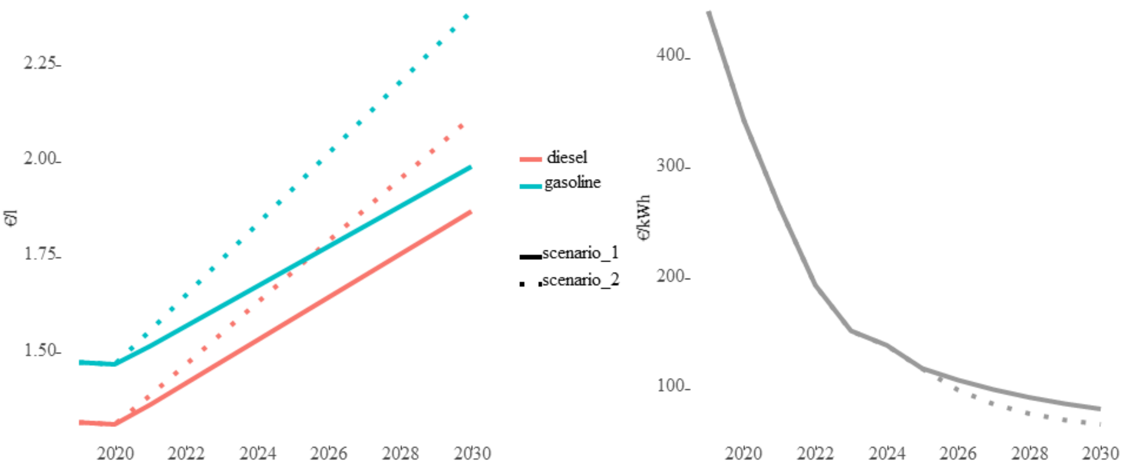

Figure 2: Key cost assumptions in the two scenarios used in this study.

Using these two background scenarios, we considered distinct grant removal options for BEVs and PHEVs:

- BEV grant removal: BEV grants are reduced first to €2500 at time 2022.5 (or 2023, 2023.5, 2024, 2024.5, 2025, 2025.5, depending on the model run) then removed altogether six months later. The same PHEV grant assumption is used in each case, i.e. reduced to €2500 at 2021.5, then removed altogether at 2022.5. The current VRT rebate for BEVs is assumed to be removed at 2022.
- PHEV grant removal: PHEV grants are reduced to €2500 at 2021.5 then removed altogether at 2022 (or 2022.5, 2023, 2023.5). The same BEV grant assumption is used in each case i.e. maintained at €5000 until 2025, cut to €2500 then removed at 2025.5. The VRT rebate for BEVs is removed at 2022.

4.2 Emissions from PHEVs

PHEV type-approval emission values (gCO_2/km) quoted by manufacturers are calculated using a standardised utility factor UF_{type} that depends on the AER of the vehicle (Eder et al., 2014):

$$e_{type} = e_{ICE}\left[1 - UF_{type}(AER)\right] \qquad [1]$$

However, a recent empirical study from ICCT (Plötz et al,. 2020) reported utility factors about half of UF_{type}, implying that PHEV emissions are systematically higher than their type-approval values.

Tailpipe emissions from a PHEV depend strongly on how the vehicle is used and will generally differ from e_{type}. At a minimum, utility factors depend not only on AER but also on mileage (m) and on the number of times per day a driver is willing or able to charge the vehicle (ξ). For real-world emissions, Equation 1 is replaced by:

$$e_{real} = e_{ICE}[1 - UF(m, \xi, AER)] \qquad [2]$$

A semi-realistic model for UF based on a distribution of daily driving distances and ξ is described in **Appendix 2**. The ICCT observations (see Figure 1 above) can be accounted for by a combination of $\xi < 1$ and higher than average mileages for PHEV adopters. In this report, PHEV emissions are modeled for a range of ξ values between 0.25 and 2, while PHEV adopter mileages are determined endogenously in the micro-simulation model described below.

4.3 Method

The method used to simulate electrification of the transport fleet is outlined in this section. The results for Ireland are described in the next section.

Over recent years micro-simulation or agent-based modeling (ABM) has emerged as a practical tool for policy evaluation. For example, micro-simulation is the principal quantitative public health policy tool used to manage the pandemic (Adam, 2020). The micro-simulation approach has also been used for exploratory studies of low-carbon technology adoption (McCoy and Lyons, 2014). ABM allows heterogeneity of a population and the effects of social interaction to be taken into account. It can provide a "policy sandbox" where alternative measures and other scenarios can be compared *ex ante* (Silverman et al,. 2020). In some cases, the method may identify deficiencies in the data or evidence base. The main disadvantages of ABM are the challenge of model calibration and computational overhead when the number of agents is $\gtrsim 1000$.

The ZEV uptake model allows heterogeneous households or "agents" to exercise car purchase decisions on a fleet of passenger cars. Detailed agent characteristics are obtained from a representative survey of 924 Irish households on attitudes to electric vehicles that was carried out in 2018 (Meles et al,. 2020). The passenger car fleet consists of 244 models available in Ireland during 2021. All five powertrain types (38 BEVs, 39 PHEVs, 16 HEVs, 87 petrol[3], and 64 diesel vehicles) and 14 distinct market segments are represented. Further details of the fleet are given in **Appendix 3**.

Simulations were initialised in January 2015, with initial ICEV fuel types (petrol or diesel) and registration years taken from the survey. A preferred market segment (e.g. compact "C" cars etc) is assigned probabilistically at the start of each run based on agent characteristics such as household size[4]. Randomization of the social network is also implemented at every run. At each monthly time step, a fixed percentage of agents (1.6% or a sample of 15 out of 924 agents) decide to replace their current car. Both new or used cars can be purchased depending on agent preference. Vehicle choice is based on the lowest total cost of ownership (TCO) over a three-year horizon[5]. Agents evaluate this for a sample of up to 10 vehicles across all powertrain types available in their segment. In the case of BEVs, there are additional social, range anxiety, and barrier (due to risk-aversion and other factors) terms. The presence of a BEV owner in the agent's social network tends to cancel out the barrier term.

Vehicle choice is not affected by an agent's previous ownership history, except that no barrier term is present for switching from a PHEV to a BEV i.e. it is assumed that a

[3] Mild hybrids, typically with batteries ~0.5kWh, are classed as ICEVs.

[4] A naïve Bayes classifier is used to assign a preferred segment to each agent. Priors are based on 2014-2019 newly licensed vehicle data adapted from CSO.

[5] The expected annual depreciation rate for petrol and diesel vehicles is taken to be 16% in Scenario 1. A slightly higher value of 17% was used for diesel vehicles in Scenario 2.

previous PHEV owner is already comfortable with electric cars. Therefore agents evaluate the switch from a PHEV to a BEV based on TCO and range anxiety only. This treats PHEVs as a potential “gateway technology” to full electrification, a feature that is sometimes argued to justify the strong policy support they receive.

5. Results

ZEV uptake and total emissions are estimated by repeated runs of the model described above (**Section 4.3**). The results in this report are based on 200 runs, found to be sufficient to reduce statistical noise to an acceptable level.

5.1 Fleet Composition

Figure 3a shows the impact of BEV grant removal timing on fleet composition to 2030 in Scenario 1. Delaying the removal of incentives increases BEV uptake in 2030 with corresponding reductions in all other powertrain types, particularly diesel and petrol. Deferring the removal of grant incentives until 2025.5 gives 22% BEV uptake at the end of 2030, compared to 19% uptake when grants are removed at 2022.5. 2030 PHEV uptake is approximately 7%. Notice that the model shows greater uptake of PHEVs compared to BEVs in the early part of the decade. However, this is not sustained.

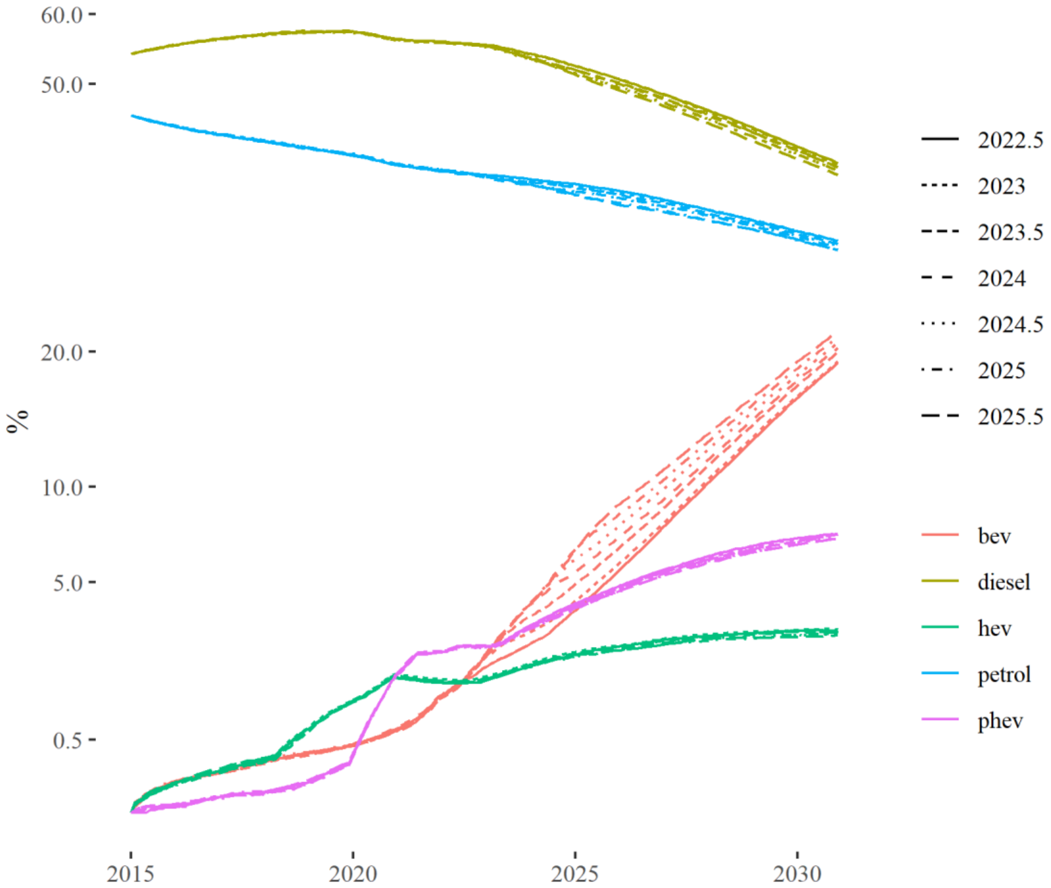

Figure 3a: Fleet composition in Scenario 1 for a range of BEV grant removal dates. Note the use of a non-linear scale on the y-axis.

Figure 3b shows the equivalent results for Scenario 2 (higher petrol and diesel prices). In this case, BEV uptake reaches 29% when grants are maintained until 2025.5, compared to 26.5% if grants are removed at 2022.5. PHEV uptake is 9% giving total ZEV uptake of 38%. PHEVs grants are removed at 2022.5.

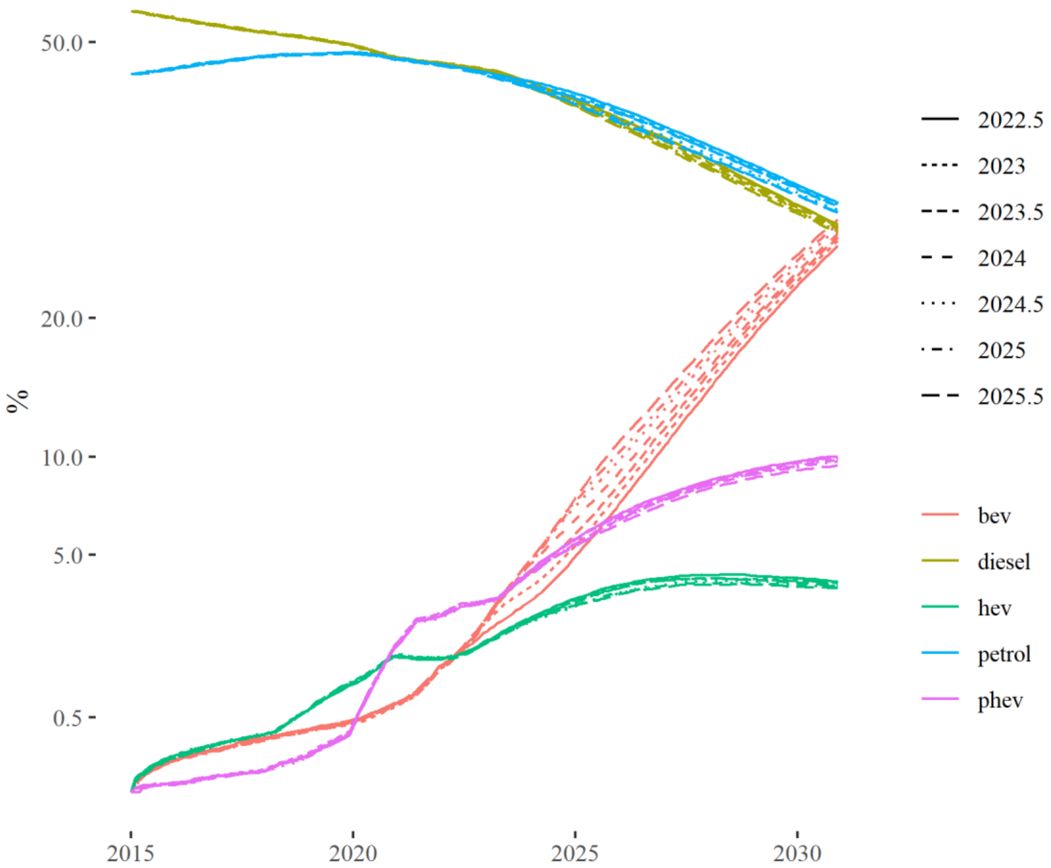

Figure 3b: Fleet composition in Scenario 2 for the modeled BEV grant removal times. BEV uptake reaches 29% when grant removal is deferred until 2025.

Figure 3c shows the impact of PHEV grant removal in Scenario 1, assuming that BEV grant is maintained until 2025. Deferring the removal of the grant (assumed reduced to €2500 since 2021.5) boosts PHEV uptake in the short-term. However, by 2030 the impact is relatively small and PHEV uptake remains close to 7%. PHEV grants are less effective in accelerating a ZEV transition that is already dominated by BEVs by 2030.

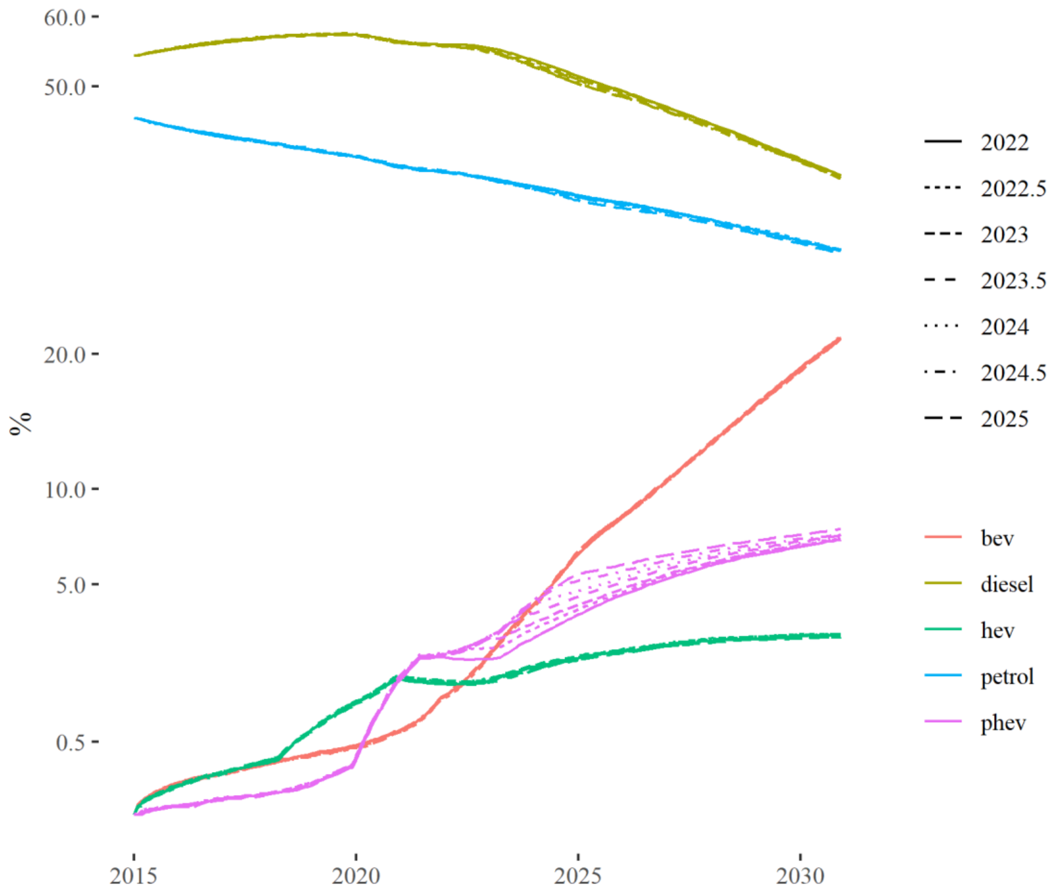

Figure 3c: Fleet composition in Scenario 1 for a range of PHEV grant removal dates.

Figure 3d shows the impact of PHEV grant removal in Scenario 2, again assuming that the BEV grant is maintained until 2025. ZEV uptake reaches 39% (10% PHEVs and 29% BEVs). Once again PHEV uptake in 2030 is relatively insensitive to the timing of incentive removals. Appendix 4 compares the projected ZEV uptake in this report with the Bloomberg New Energy Finance forecast.

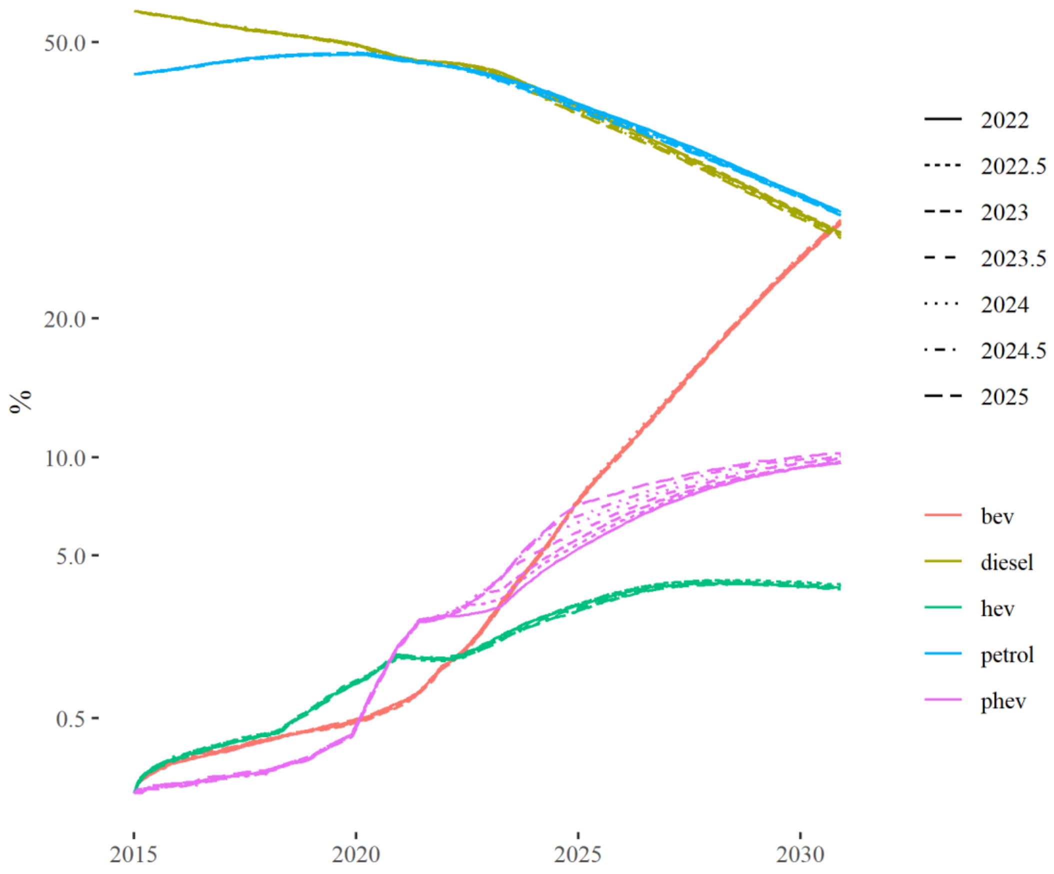

Figure 3d: Fleet composition in Scenario 2 for a range of PHEV grant removal timings.

5.2 Emissions

Figure 4 shows the average emissions per vehicle in the passenger car fleet for 2015-2030 in Scenario 1 and Scenario 2. Emissions at the start of 2021 are 2.35 tCO_2 per vehicle, falling to 1.33tCO_2 at the end of 2030 in Scenario 2 when grants are maintained until 2025.5.

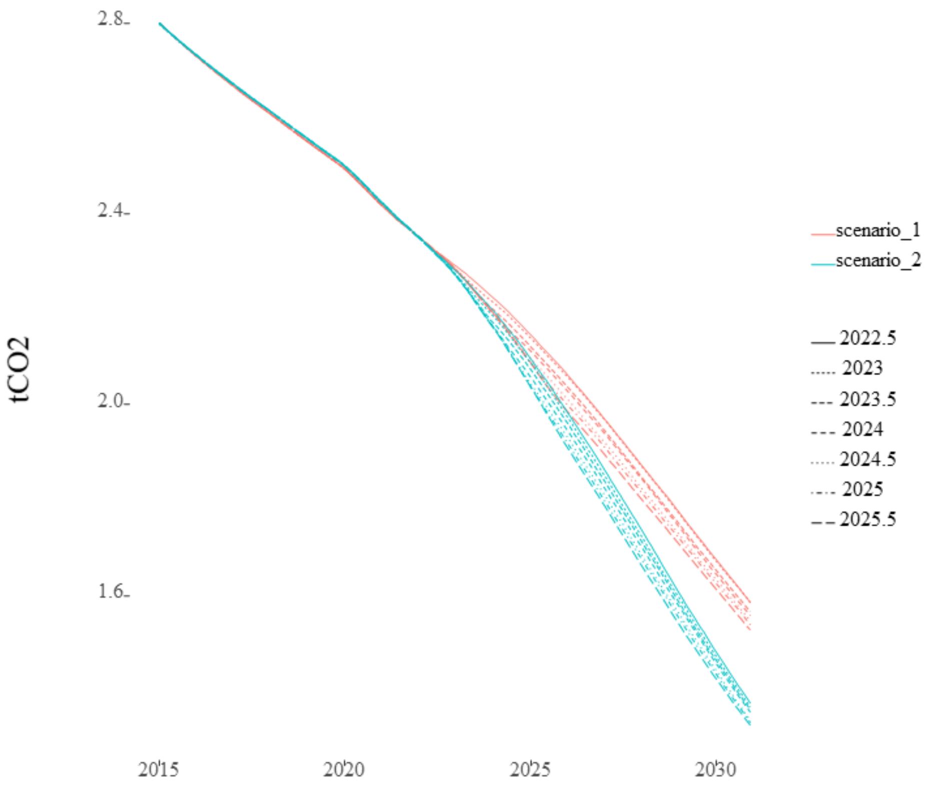

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Figure 4: Fleet average emissions per vehicle in Scenario 1 and Scenario 2 for the range of BEV grant phaseout times. PHEVs are assumed to be charged once per day.

It is important to note that emissions values quoted in this report are based on ICEV WLTP values. These may still be 15% lower than real-world emissions.

5.3 Incentive Costs

The relative cost-effectiveness of incentives (€/tCO_2) for PHEVs and BEVs can be compared. Figure 5a shows that cumulative emissions versus cumulative BEV incentive costs for the decade 2021-2030. Each point on this graph represents 200 model runs for a particular BEV phaseout time. Emissions fall as BEV grant removal is deferred but total incentive costs increase. The error bars indicate statistical noise (95% confidence intervals). The convexity of these curves means that €/tCO_2 costs increase when BEV grants are maintained for longer. This is expected because BEVs adopted later in the decade contribute less to cumulative emissions reduction. Also, BEVs adopted earlier increase later uptake by lowering the barrier for potential BEV adopters. The x and y-axis scales assume a constant passenger car fleet of 2.1 million vehicles (AECOM, 2019). With this assumption, the cost of maintaining the €5000 BEV incentive until 2025.5 is close to €800M. Note that the Scenario 1 curve is somewhat steeper, reflecting slightly higher costs for Scenario 2.

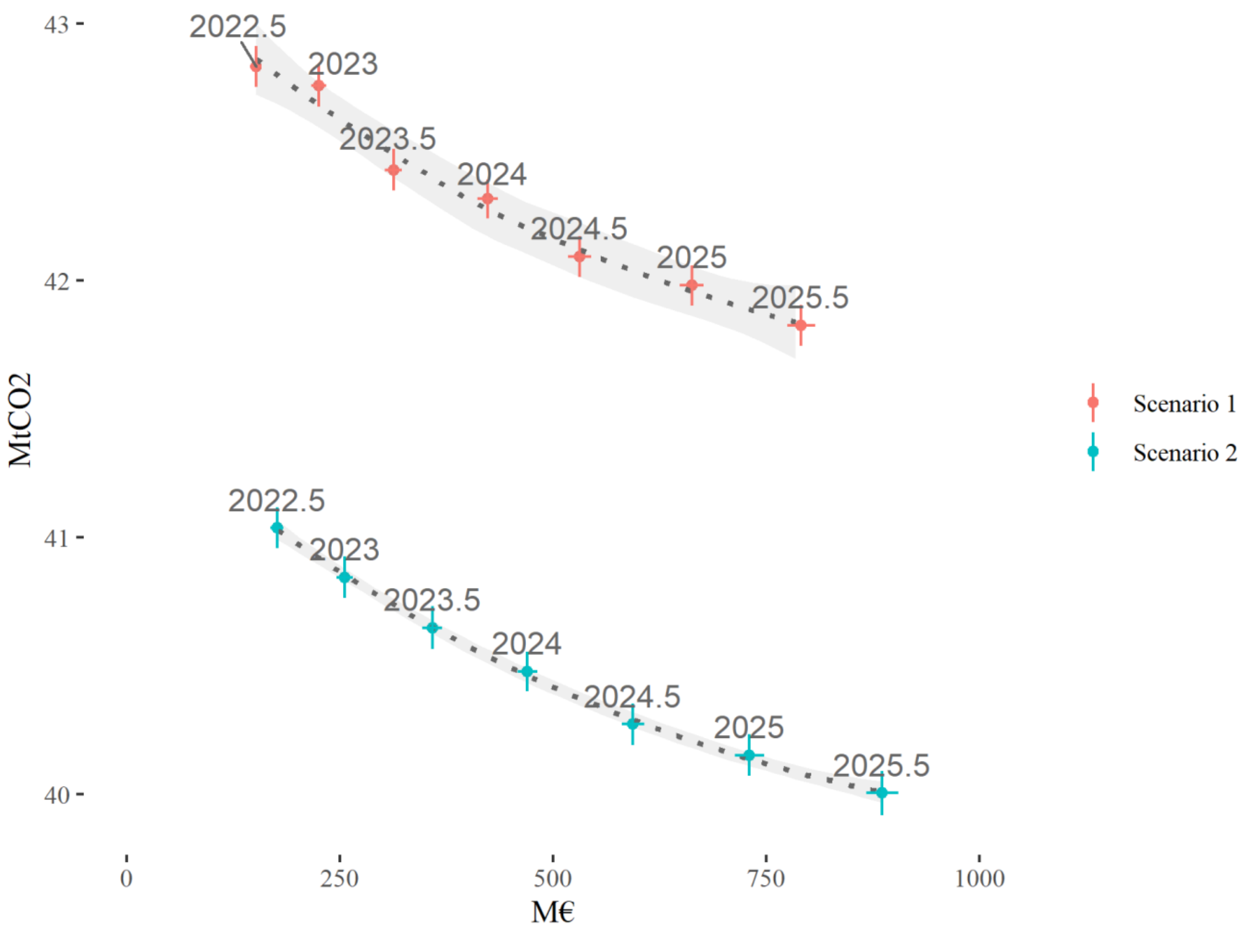

Figure 5a: Cumulative emissions vs incentive cost for BEV grants in scenarios 1 and 2. Each data point corresponds to 200 model runs for the BEV grant phaseout time indicated. PHEV emissions are modeled with ξ=1. The scales of the x and y-axes assume a constant passenger car fleet of 2.1 million vehicles.

Figure 5b shows the same graph for PHEV incentives (in this case €2500) in Scenario 1. This time emissions are shown for a range of charging frequencies ξ. Emissions reductions are very sensitive to charging frequency, as vehicles that are charged less frequently emit more. Indeed for $\xi = 0.25$, the curve is almost flat and incentives have little impact on cumulative emissions. The absolute cumulative cost of PHEV incentives is lower than for BEVs because the grant amount is lower, uptake is lower and they are removed sooner in the grant phaseout scenario. Figure 5b indicates that improving PHEV owner charger behaviour may be a more effective way to decarbonise transport than maintaining grants for longer.

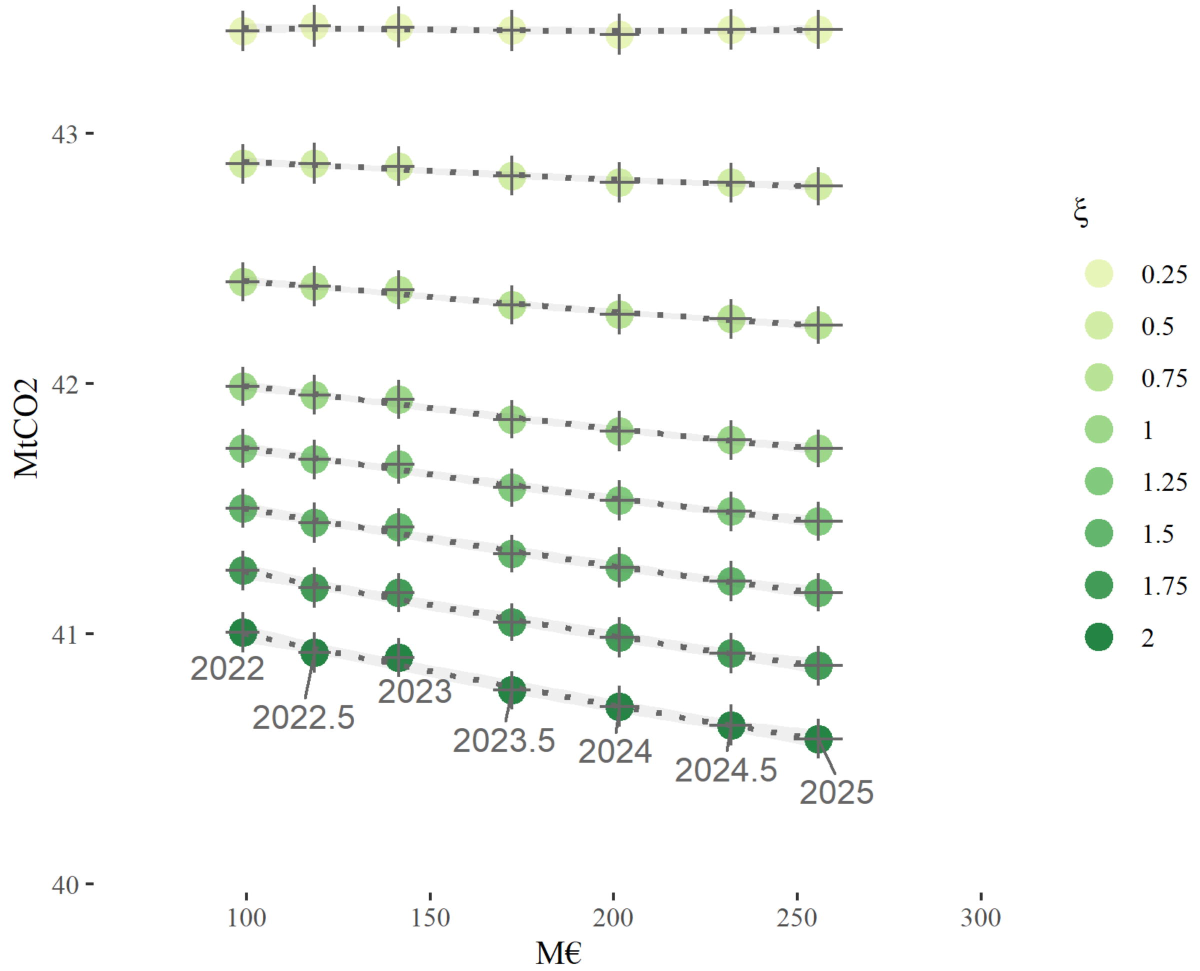

Figure 5b: Cumulative 2021-2030 emissions versus cumulative incentives in Scenario 1. A constant passenger car fleet of 2.1M vehicles is assumed. The impact of grants on emissions depends strongly on charging behaviour. Grants are ineffective when PHEVs are charged infrequently.

Tables 2a summarises € cost per tCO_2 implied by Figures 5a and 5b for Scenario 1. PHEV costs per tCO_2 are highly sensitive to ξ, rising rapidly when $\xi < 1$. Even for $\xi = 1$, PHEV €/tCO_2 costs are higher than for BEVs. However, if $\xi = 2$, PHEV costs are lower than the equivalent BEV cost. The reason this occurs is that PHEV uptake is greatest for higher emissions high mileage drivers, while the opposite is the case for BEVs. BEV costs per tCO_2 increase when the incentives are maintained for longer but PHEV costs rise more slowly relative to BEVs.

Table 2a: Costs in €/tCO_2 of extending BEV and PHEV incentives in Scenario 1.

grant removal date	€/tCO_2					
	BEV			PHEV		
	$\xi = 0.5$	$\xi = 1$	$\xi = 2$	$\xi = 0.5$	$\xi = 1$	$\xi = 2$
2022.5	-	-	-	1429	580	345
2023	400	416	437	1446	585	348
2023.5	420	437	460	1470	592	353
2024	444	463	488	1488	598	358
2024.5	489	511	540	1509	605	363
2025	541	565	596	1529	610	367
2025.5	597	620	650	-	-	-

Table 2b shows the equivalent results for Scenario 2. Costs are higher in this scenario because of increased uptake of ZEVs and lower cumulative emissions (Figure 5a)[6].

Table 2b: Costs in €/tCO_2 of extending BEV and PHEV incentives in Scenario 2.

grant removal date	€/tCO_2					
	BEV			PHEV		
	$\xi = 0.5$	$\xi = 1$	$\xi = 2$	$\xi = 0.5$	$\xi = 1$	$\xi = 2$
2022.5	-	-	-	1228	590	373
2023	426	452	484	1277	603	380
2023.5	454	481	513	1348	622	391
2024	489	517	550	1413	639	401
2024.5	539	565	597	1468	652	408
2025	589	620	659	1560	674	420
2025.5	651	694	753	-	-	-

[6] Note that, if WLTP emissions values are 15% lower than real-world values, then Tables 1a & 1b over-state the actual cost of emissions reduction by 15%.

What is the correct value of ξ? While the ICCT report suggests that $\xi < 1$, there is limited direct evidence on the appropriate value for Irish PHEV drivers. Table 3 shows that the number of SEAI home charger and ZEV purchase grants made during 2018-2019[7]. PHEV owners appear as likely to apply for a home charger grant as BEV owners, and therefore there is no indication that these early adopters did not intend to charge their PHEVs at the time of purchase. Of course, there may be a difference between early and later adopters who are responding to stronger tax incentives rather than e.g. environmental concerns.

Table 3: SEAI grant numbers for private cars 2018-2019.

	Purchase grants	**Charger grants**
BEV	2413	2525
PHEV	1431	1634

Another approach to gauging ξ is to compare UFs from the micro-simulation model with international values given by ICCT. Figure 1 (see **Section 2.2**) shows a uniform distribution of utility factors below the type-approval values. Figure 6 shows simulated UF values for PHEV adopters up to 2025 (40 simulation runs in Scenario 2). Higher average mileages of PHEV adopters cause the distribution of UF values to be skewed below UF_{type} values shown in grey. This is similar to the data from ICCT. From these graphs, the uniform distribution of UF values below type-approval observed by ICCT suggests a range between 0.7-1.0. Values as low as 0.5 seem less likely.

[7] Data kindly provided by SEAI.

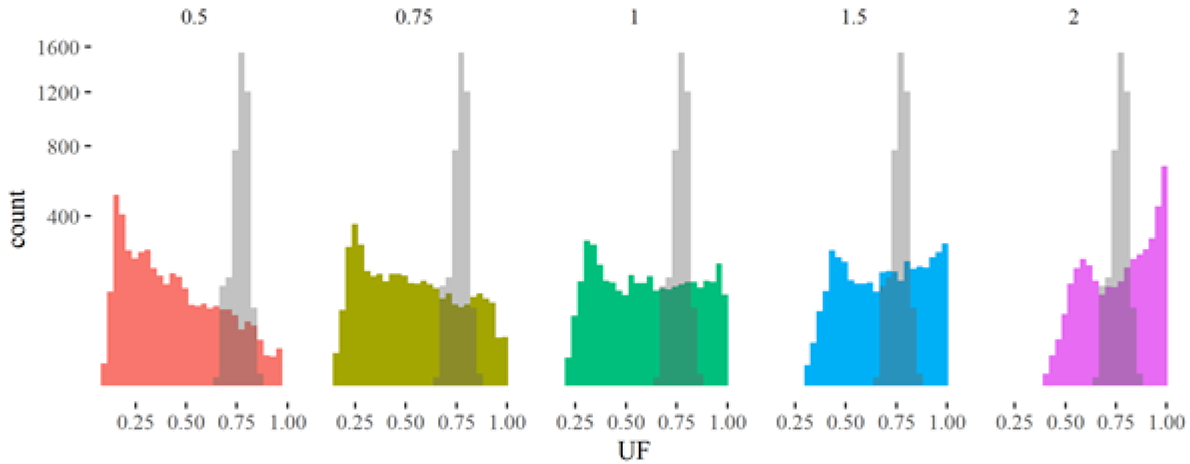

Figure 6: Histograms of simulated utility factors of PHEV adopters during 2015-2025 for a range of ξ values. The grey histogram corresponds to the type-approval UF values of the vehicles. 40 runs in Scenario 2.

Data needs to be collected on the charging habits of Irish PHEV drivers. An important question is the extent to which the availability of charging infrastructure and higher transport fuel prices can encourage higher ξ, reducing PHEV emissions significantly (Figure 5b).

5.4 BEV-PHEV Competition and Market Segmentation

Figure 7 illustrates the role of market segmentation in the ZEV transition. Uptake by powertrain type and market segment is shown as a percentage of the total fleet. Note that there is a particularly strong uptake of BEVs in the “C” segment due to the appearance of price-competitive models such as the ID.3. However, PHEVs dominate in the executive car “E” and large SUV “D-J”, although BEVs are beginning to compete even in these segments by 2030. Competition between PHEVs and BEVs is most evident in the “C” crossovers. There are several vehicle types notably multi-purpose vehicles and people carriers (“M”) where ZEVs are absent entirely or uncompetitive. Manufacturers will likely fill these gaps in the coming years but they do not appear in the model outputs since there are few or none of these vehicle types currently in the market.

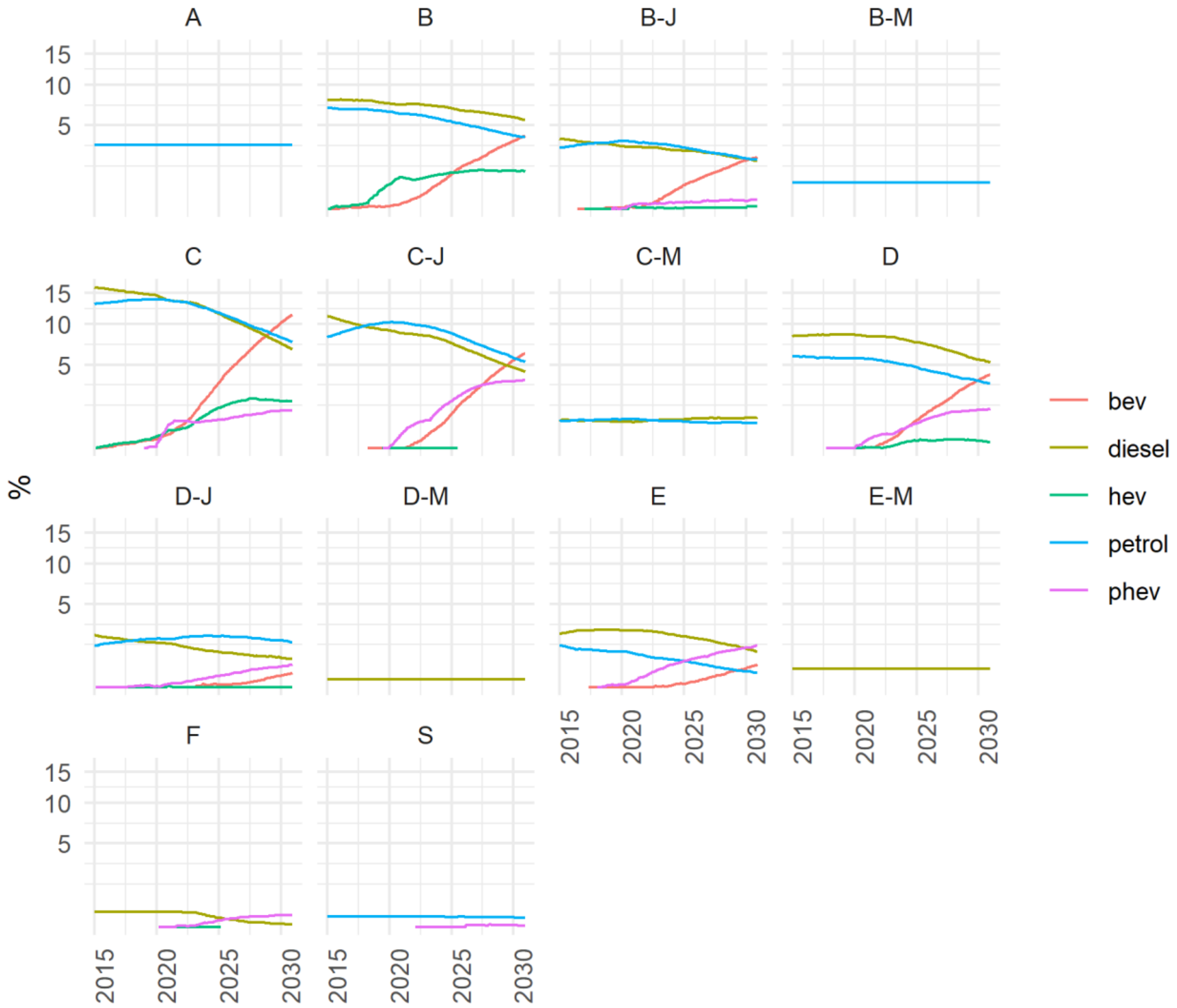

Figure 7: 2015-2050 uptake by market segment in Scenario 2 with BEV grants maintained until 2025.

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Appendix 1: Overview of subsidies introduced in the EU

(Amended from the European Automobile Manufacturers Association (ACEA), 2013; ACEA, 2020).

	Purchase Subsidies	Non-fiscal Incentives	Tax Benefits		
			Registration Tax Benefits	Ownership Tax Benefits	Company Tax Benefits
Austria	€2,500 per PHEV with a petrol combustion engine (€1,250 by the federal government; €1,250 additional rebate by industry). Purchase price must not be over €50,000 (including VAT) and minimum electrical range of 50km.	Several bigger cities in Austria have exemptions from parking charges	Vehicles below 118 g/km^{-1} are registration tax-free.	PHEV users pay circulation tax (motorbezogene Versicherungssteuer). This tax is calculated on the basis of the engine's horsepower and owners only pay for the ICEV part.	The In-kind benefits for the private usage of company cars is taxed with 0%. PHEVs and cars <141 g/km^{-1} are taxed with a lowered tax of 1.5%, all cars above 141 g/km^{-1} are taxed with 2% (the threshold comes down 3 g/km^{-1} every year until 2026).
Belgium			In Flanders, PHEVs are exempted from vehicle registration tax benefits until 2020. In Wallonia and the Brussels Capital Region there is a minimum vehicle registration tax of €61.50.	In Flanders, PHEVs are exempted from ownership tax benefits until 2020.	
Bulgaria	PHEVs receive a 15% VAT reduction in cost when purchasing a new vehicle.			Vehicles with an engine power not exceeding 74 kW, including those meeting the Euro 3 and Euro 4 requirements have a reduced annual tax of 50%, vehicles that meet the requirements of Euro 5 and Euro 6 receive a reduction of 60%.	

Croatia	Once a year, limited funds of €4,600 for PHEVs				
Cyprus			Vehicles with emissions less than 120 $gCO_2\,km^{-1}$ are exempt from paying registration taxes	Any tax reductions and/or exemption are based on CO_2 based taxes	
Denmark			PHEV are granted a reduction in the calculated registration tax of up to DKK 40,000 in 2020. The registration tax cannot be negative and the minimum tax. PHEVs are granted a reduction in the taxable value of the car for battery capacity of DKK 1,700/kWh until the end of 2022. The capacity is a calculated figure based on electric consumption and electric range. All consumption figures will be based on WLTP as of 1 January 2021.	For circulation taxes, PHEVs pay less than an equivalent diesel or gasoline car. In 2020 a temporary deduction in the annual taxation of DKK 40,000 (3,333 per month) is granted for PHEVs, but only temporarily during the period from 1 April 2020 until 31 December 2020.	
Finland	Scrapping schemes run every couple of years (2015, 2017 and 2018) by the Finish Government that offer individuals bonuses of up to €2000 for scrapping old diesel/gasoline vehicles and buying new PHEVs.				

France	Purchase grant of up to €2,000 for PHEVs emitting between 21g – 50 gCO_2/km^{-1}. Scrappage scheme (conversion bonus): up to €5,000 for the purchase of second hand or new PHEVs if you get rid of your diesel car (older than 2001) or gasoline car (older than 1997).		PHEVs are eligible for either a 50% discount or are fully exempt from paying the license plate registration (carte grise) in Metropolitan France depending on the region. An environmental penalty is enforced as a registration tax, starting from 138 gCO_2/km^{-1} - WLTP standard (131g in 2021 and 123g in 2022). The maximum rate for cars with more than 225 gCO_2/km^{-1} currently amounting to 20,000 euros. According to the current draft budget, the maximum rate is to be doubled again in 2021 to €40,000 and then increased to €50,000 in 2022. All vehicles under 138 gCO_2/km^{-1} are exempt from this tax Registration Regional Tax - Most regions 100% discount, some 50% some 0%"		
Germany	Until 31 December 2021, an 'innovation bonus' temporarily increases the environmental bonus for new and used PHEVs. Applies to all eligible vehicles registered from 4 June 2020. Bonus for cars with net list price ≤€40,000: €6,750 for PHEVs. Bonus for cars with net list price >€40,000: €5,625 for PHEVs. This criteria for the latter also include a maximum emission value of 50 gCO_2/km^{-1} or an electrical range of		Kfz-Steuer (motor vehicle tax) – PHEVs pay this tax, butat a lower rate than diesel/gasoline vehicles, in proportion with their lower CO_2 emissions. VAT fell from 19 to 16% between 1 July - 30 December 2020. This tax incentive benefits PHEVs.		As part of the package of financial incentives approved in 2016, private owners of plug-in electric vehicles that charge their cars in their employer premises are exempted from declaring this perk as a cash benefit in their income tax return. Employers who provide this perk are allowed to discount from their income tax a 25% of the lump sum value of the cash benefit. These two fiscal benefits apply only from 1 January 2017 until the end of 2020.

	at least 40km. This range requirement applies until 31 December 2021, subsequently it will be increased to 60km. From 1 January 2025 it will increase to 80km. Under the ‘Umweltbonus’ (environmental bonus) program there are purchase grants: ● For vehicles priced up to €40,000: PHEVs: €6,750 ● For vehicles priced up to €65,000: PHEVs: €5,625				
Greece	15% cashback for PHEVs with ≤50 gCO_2km^{-1} of up to €8,000, plus extra €2,500 if an old taxi is scrapped. 15% cashback for vans (up to €4,000 for PHEVs), plus €1,000 for scrapping.		Hybrid cars with a higher engine capacity pay 60% of the normal circulation tax rate		
Hungary			PHEVs, like all cars, pay vehicle tax and transfer tax regressively, based on the age of the vehicle, and its engine power.		
Italy	Subsidies of up to €3,500 for vehicles that emit between 21 and 60 g/km^{-1} for individuals and companies. Bonus - malus scheme: A one - off amount (max €6,000 for cars emitting ≤70g CO_2km^{-1} and a price less than €50,000 (excluding VAT). Malus: up to €2,500 for cars emitting more than 250 gCO_2km^{-1}. Hybrids with CO_2 emissions of between 21 and 60 grams per kilometre will be subsidized with	Free access to the LTZ and free parking in many urban centres for PHEVs. According to Italian budget law for 2020, public administrations when renewing their fleet have to	PHEVs have ownership tax exemption from the annual registration tax for five years after they have purchased their vehicle. After this five-year period, they benefit from a 75% reduction of the equivalent tax rate for most petrol vehicles.		

	€3,500 or €6,500 if an old car is decommissioned at the same time. These rates were previously €1,500 and €2,500 respectively. The increased incentives are financed partly by the state and partly by the car manufacturers.	reserve a 50% quota for the purchase or rental of electric, hybrid or hydrogen vehicles.			
Lithuania		Free parking for PHEV with special EV registration numbers in cities including Kaunas, Klaipėda, Panevėžys, Šiauliai, Neringa.	Registration tax exempt if emissions do not exceed 130 gCO_2km^{-1}.		
Luxembourg	Purchase subsidies of up to €2,500 for PHEVs emitting <50 gCO_2km^{-1}.			Any tax reductions and/or exemption are based on CO_2 based taxes.	Any tax reductions and/or exemption are based on CO_2 based taxes.
Malta			Registration tax of vehicles is based on length of vehicles, emissions and age.		
Nether	Taxes for gasoline and diesel will be increased by one cent per litre in 2020 and will see another one-cent increase in 2023.		PHEVs pay a reduced fee for purchase tax (BPM) based on their emission levels.	High-emitting CO_2 vehicles that are more than 12 years old have to pay an additional 15% on top of existing ownership tax as of 2019.	

lands				Until 2024, PHEVs get a 50% discount on ownership tax (MRB). In 2025, PHEVs will pay 75% of the tax.	
Norway			In 2017, the incentives for PHEVs were increased. In particular, the deduction on the total weight to be used for the determination of the taxation rate increased from 15% in 2015 to 26% in 2017. For large PHEVs this change leads to registration tax cuts of NOK 16,000-80,000 (€1,700-8,400) compared with similar ICEVs.	PHEVs are granted a reduction and pay the minimum amount	
Poland			PHEVs are exempt for purchasing tax until the beginning of 2021.		
Portugal	Purchase subsidy for PHEVs of €1,125.			Any tax reductions and/or exemption are based on CO_2 based taxes.	VAT is deductible for companies (With acquisition cost <€ 50,000€+VAT for PHEVs)
Romania	Renewal scheme (RABLA) for passenger cars: - €4,250 to buy a new PHEV with ≤50g CO_2/km. - In addition, €1,250 for scrapping an old vehicle.		PHEVs are exempt from registration tax.	Any tax reductions and/or exemption are based on CO_2 based taxes.	

Slovakia	Until the end of 2018 there was a grant of €3,000 for a PHEV available (buying before June 2018)				
Slovenia	€4,500 for PHEVs (cars and vans)				
Spain	Incentive scheme (MOVES Plan): Cars: €1,900 - €2,600 for PHEVs for private individuals, depending on whether a vehicle older than seven years is being scrapped. Vans and trucks: between €4,400 and €6,000 for private individuals, depending on scrapping. Grants for purchase or lease: PHEV (40 km range or more): €2,600 (max. list price: €45,000)				
Sweden	'Climate bonus' - SEK 10,000 for PHEVs emitting less than 60 gCO_2km^{-1}. The bonus has to be a maximum of 25% of the car's (new) purchase price.			Vehicles are subject to an annual circulation tax based on weight and gCO_2km^{-1}. "Super green" cars are exempt for the first five-years after registration.	

UK	**Buyers can receive a** Plug-in Car Grant up to 35% of the cost of an electric car (up to a maximum of **£3,000** depending on the model). PHEVs must have CO_2 emissions of less than 50g/km and can travel at least 112km (70 miles) without any emissions. The Scottish Government offers an interest-free loan to support drivers switching to a BEV or hybrid car. Loans of up to £35,000 to cover the cost of purchasing a new electric/hybrid vehicle, repaid over a period of 6 years.	EVs and PHEVs are exempt from London's Congestion Charge scheme until 2025.			PHEVs emitting less than 50 gCO_2km^{-1} have their company car tax set at 16% in 2020, which is 4-8% lower than the tax on diesel company vehicles.

Appendix 2: Utility Factor Model for PHEVs

This appendix provides further details of the "real-world" PHEV emissions estimate that is used in the micro-simulations to compute transport emissions. PHEV utility factors depend on the statistical distribution of daily driving distances[8] e.g. Figure A1.

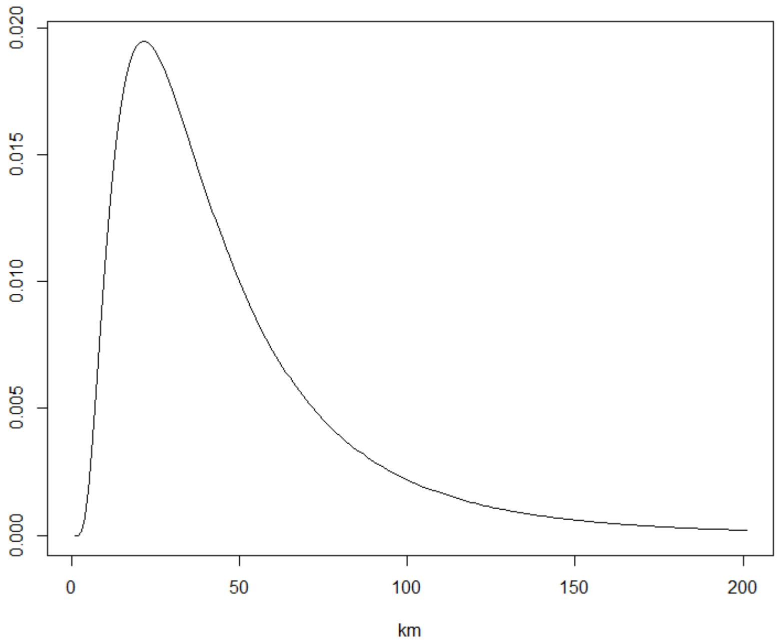

Figure A1: Distribution of daily driving distances for annual mileage 15,000km and 6 days per week vehicle use.

By sampling daily distances generated from this distribution, PHEV battery charge states can be calculated, depending on AER and the assumed value of ξ. The resulting family of utility factor curves is shown in Figure A2. For example, $\xi = 2$ means that the driver charges his vehicle twice per day whenever necessary so that only trips that exceed 2AER lead to charge-depleted driving and generate tailpipe CO_2 emissions. In that case, Figure A2 shows that only vehicles driven with more than twice the annual mileage have UF below their type approval value. Conversely, when $\xi = 0.5$ even vehicles *with* average annual mileage have $UF < UF_{type}$.

[8] Daily driving distances are taken to be lognormally distributed with standard deviation σ= 0.65. https://www.sciencedirect.com/science/article/pii/S0191261516309067

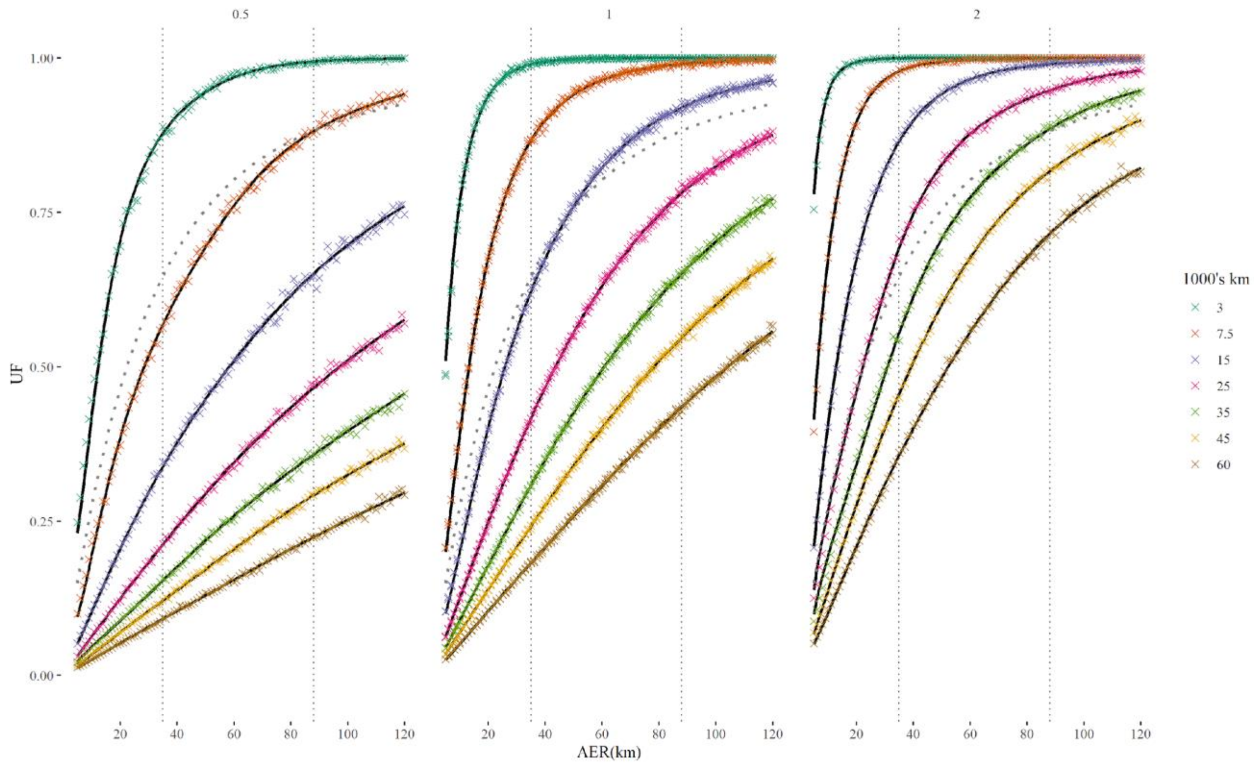

Figure A2: Simulated utility factors over 5000 days for a range of mileages and charging frequency 0.5,1,2. The solid lines are 10th order polynomial fits to $log(1-UF)$ accurate over the entire AER range (5km-250km). The dotted curve is the type-approval utility factor that is independent of mileage and ξ. Vertical dotted lines show the range of PHEV AERs present in the 2021 new car fleet.

An alternative way to visualize PHEV utility factors is shown in the heat maps of Figure A3. These show UF as a function of ξ (y-axis) and annual mileage (x-axis). Green areas represent regions of the parameter space where $UF > UF_{type}$ and brown areas represent $UF < UF_{type}$. The first plot corresponds to PHEVs with AER=35km (e.g. Volvo XC90). This has a smaller green area compared to the third plot with AER=85km (e.g. BMW X5). However, even in the latter case, infrequent charging would mean that a driver with average mileage has emissions above UF_{type}.

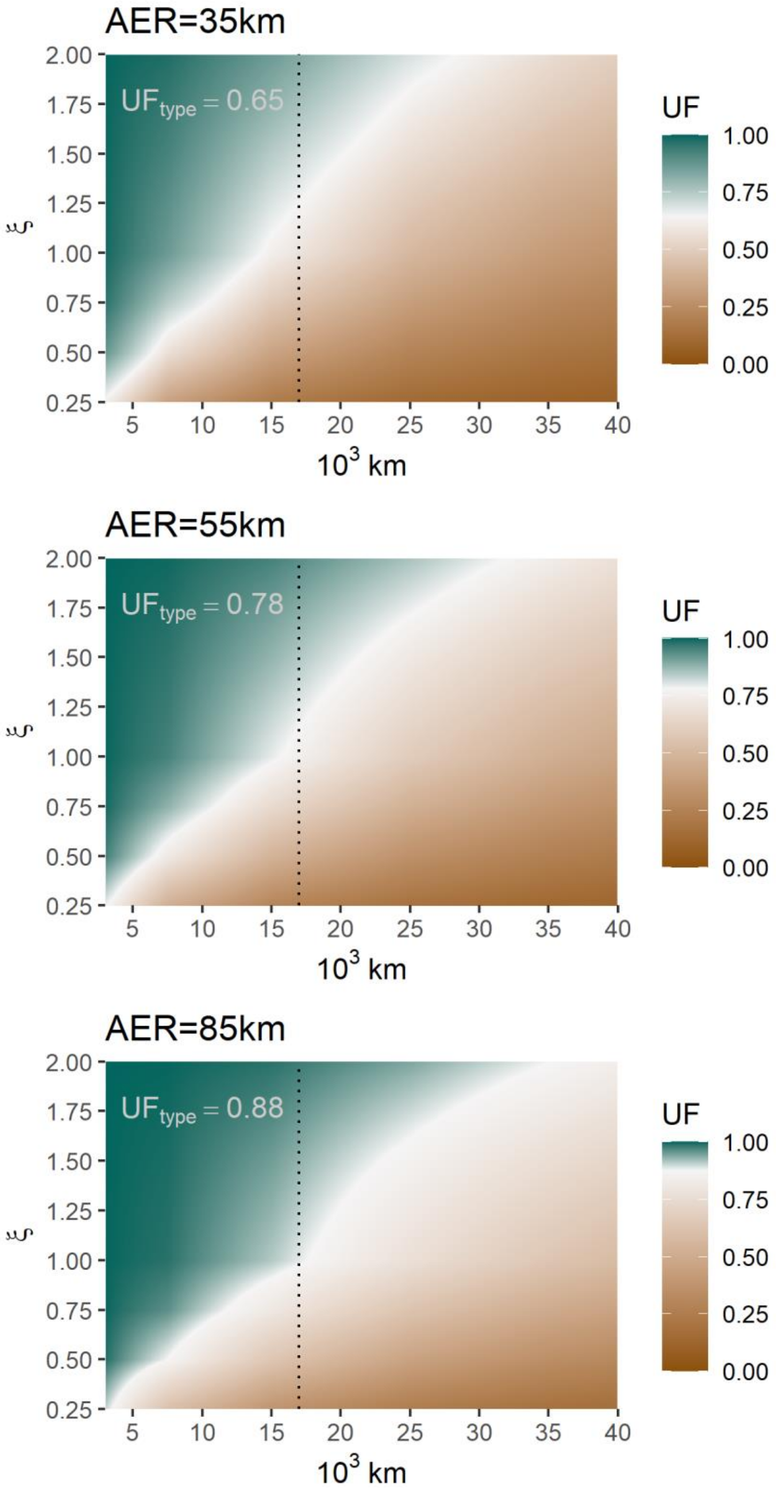

Figure A3: Heat maps showing real-world utility factors as functions of charging behaviour (ξ) and annual mileage. In the green area, real-world utility factors exceed type-approval UFs. Conversely, utility factors fall below type-approval values in the brown areas. Mean annual mileage (17k km) is indicated by a dotted line.

Appendix 3: 2021 New Car Fleet

This appendix provides details of an up-to-date 2021 new car fleet dataset that was constructed for this analysis and used as the basis for forecasting consumer adoption of ZEVs. The diversity of ZEVs is far higher than in previous years. The 2021 fleet is projected forward and backward in time with appropriate technical parameters and cost adjustments, depending on the chosen scenario. The year of introduction of electric models is used to ensure that only available ZEVs can be adopted. The dataset is also supplemented with earlier BEV versions with low battery capacities. These are absent as new cars but are still available to buyers of used cars (e.g. the 24kWh Nissan Leaf).

Table A1 summarises the number of car models present by market segment and powertrain type. BEVs are concentrated in the sub-compact "B" and compact "C" segments. There are a relatively larger number of PHEVs in the large car and crossover ("J") segments. No electrified MPVs ("M") or city car "A" options are present.

	A	B	B-J	B-M	C	C-J	C-M	D	D-J	D-M	E	E-M	F	S	*Total*
Petrol	5	14	16	1	17	14	3	6	3	0	3	0	1	4	*87*
Bev	0	10	7	0	7	7	0	3	2	0	2	0	0	0	*38*
Diesel	0	3	8	0	13	15	3	8	8	2	2	1	1	0	*64*
Hev	0	1	3	0	4	4	0	2	1	0	0	0	1	0	*16*
Phev	0	1	6	0	5	7	0	6	7	0	5	0	1	1	*39*
Total	*5*	*29*	*40*	*1*	*46*	*47*	*6*	*25*	*21*	*2*	*12*	*1*	*4*	*5*	*244*

Table A1: Numbers of vehicle models by segment and powertrain type in the 2021 new vehicle dataset used in this study.

Figure A4a shows vehicle cost (i.e. dealer prices net of taxes and grants) vs gross battery capacity (kWh) for ZEVs in the dataset. There is a clear separation between PHEVs and BEVs. BEV costs correlate with battery size[9] as expected.

Figure A4b shows AERs (km) versus gross battery capacity (kWh). BEV AERs correlate with battery capacity as expected[10]. This is not the case for PHEVs. This suggests that manufacturers increase PHEV battery capacity primarily to overcome the effects of larger vehicle mass (Table A2) rather than to extend AER much beyond

[9] For "C" segment BEVs, the slope of the graph corresponds to 264€/kWh.

[10] The slope corresponds to conversion efficiency e.g. 0.16kWh/km and 0.15kWh/km for "C" and "B" segment BEVs respectively.

60km. A PHEV with an AER of 60km has type-approval utility factor $UF_{type} = 0.8$. This means that it can be equipped with a 250gCO2/km ICE yet still achieve type-approval emissions of 50gCO2/km.

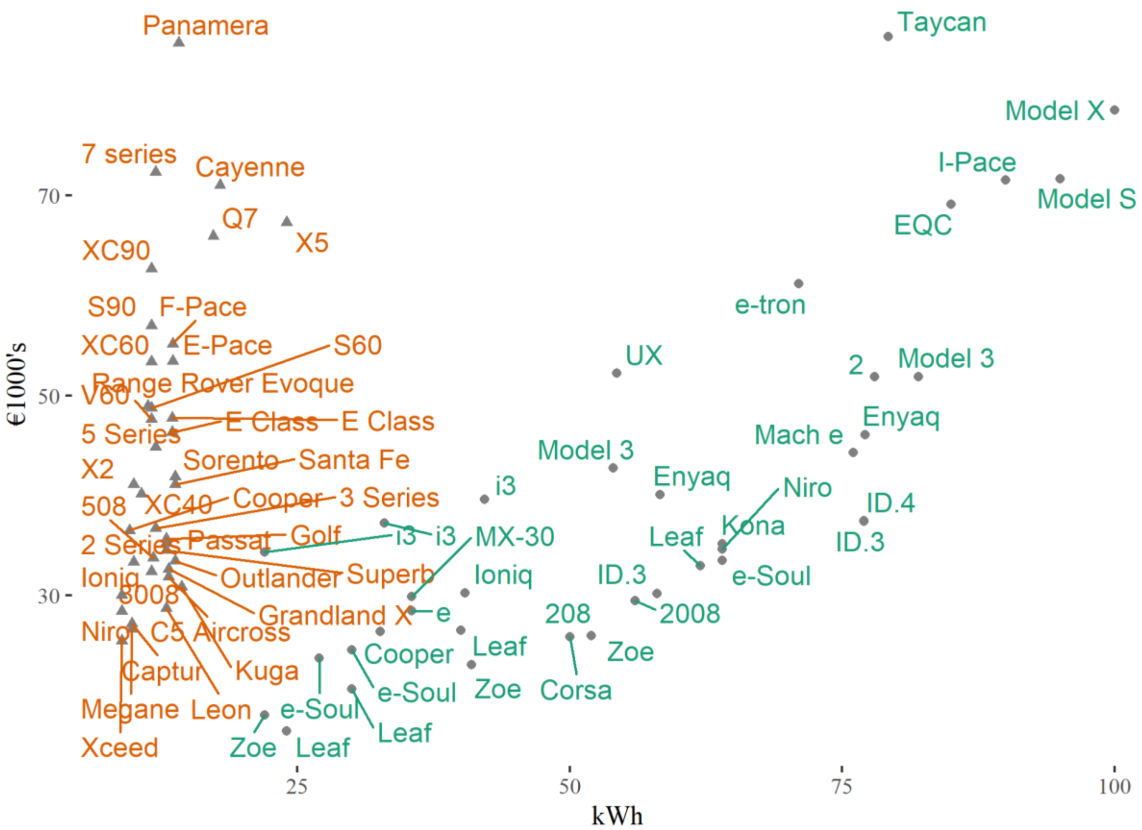

Figure A4a: Technology cost vs battery capacity

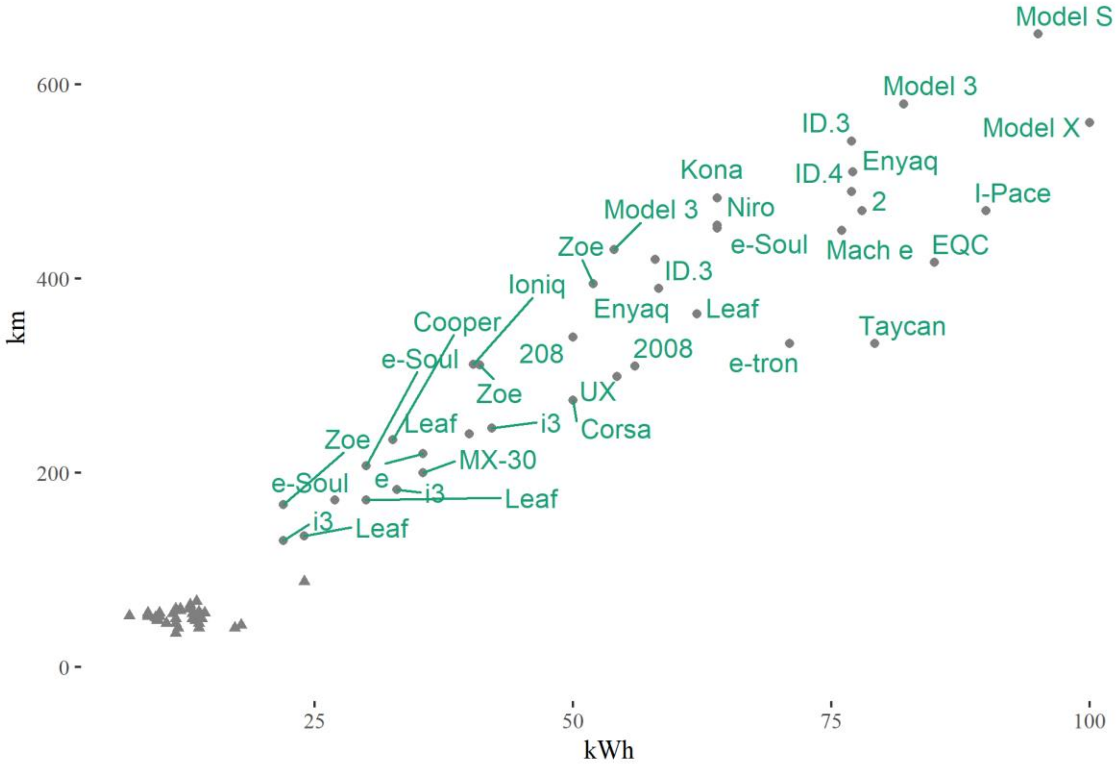

Figure A4b: AER vs kWh for ZEVs in the 2021 fleet dataset.

Appendix 4: Comparison with BloombergNEF projections

Bloomberg New Energy Finance produces an influential report[11] projecting ZEV market share of new car sales. Their report provides a useful point of comparison for the micro-simulation results for Ireland described in this report. Figure 2 shows ZEV annual sales market shares out to 2050 in Scenario 1 and Scenario 2. It is assumed that the BEV grant is maintained until 2025, and the PHEV grant is removed at 2022.5. Otherwise, no new policies (such as ICEV bans) are introduced post-2030.

For new car purchases, simulated market share exceeds the BNEF curve in the early part of the current decade, likely reflecting strong policy support. This situation continues in the second half of the decade in Scenario 2. Post-2030, the simulations show lower uptake, probably due to more optimistic technology cost assumptions used by BNEF. In the case of used car sales (bottom graphs in Figure A5), the distorting effects of incentives are less apparent, and the market shares of BEVs are closer to the BNEF curve.

[11] Electric Vehicle Outlook 2020 https://about.bnef.com/electric-vehicle-outlook-table-of-contents/

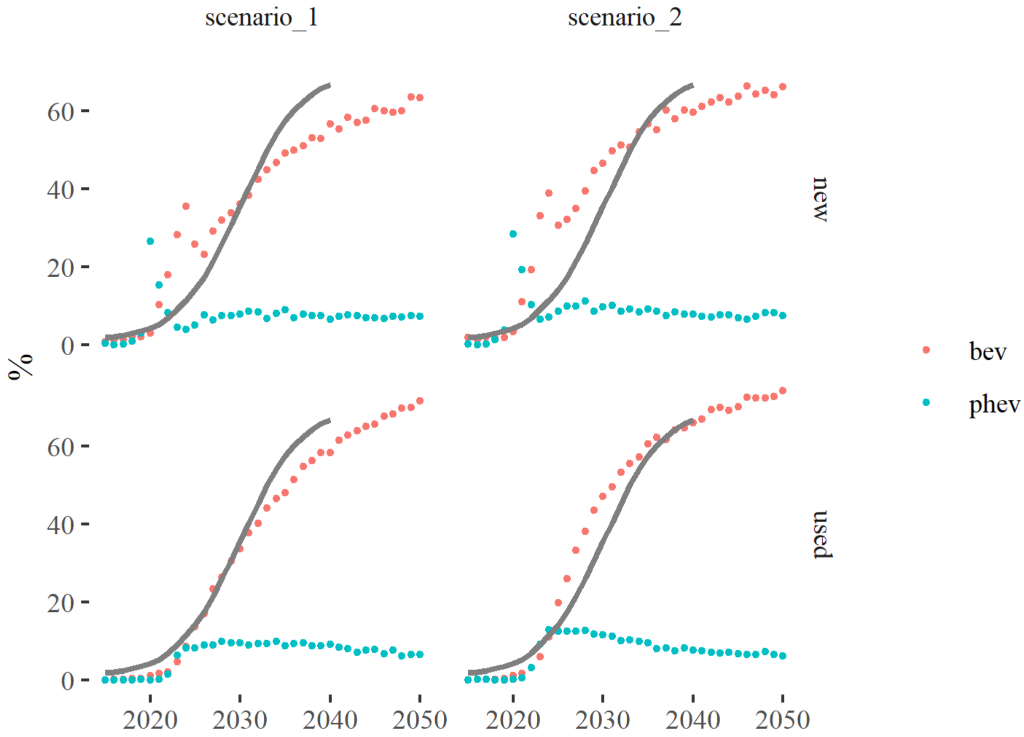

Figure A5: Market share of BEVs and PHEVs compared to BNEF 2020 (solid curve). The top (bottom) panels show shares of new (used) ZEV sales in scenarios 1 and 2. Data based on 40 model runs to 2050.

Note that the simulations predict that PHEV market share exceeds BEV market share in the early years of this decade. This has been observed for the first time in January 2021[12].

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12 https://www.irishtimes.com/news/environment/electrified-vehicles-see-sharp-rise-in-sales-under-new-tax-scheme-1.4492165