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How feasible is unprecedented? Modelling diffusion pathways for ambitious climate policy targets

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Working Paper 01-2021

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Contents

Abstract

This paper presents a novel use of the Bass diffusion model together with a new greenhouse gas (GHG) emissions model for Ireland. The approach provides a robust framework to understand technology diffusion pathways, enables international comparison and feasibility assessment of policy targets, and delivers policy insights tailored to innovation adopter categories. The GHG emissions model is developed using the Low Emission Analysis Platform (LEAP), applying a detailed bottom-up design methodology. The scenario analysis explores the impacts of two key Irish climate policy targets for 2030: (1) the introduction of 840,000 electric vehicles (EV) and (2) the retrofitting of 500,000 residential dwellings (representing ~40% of current car stock and ~30% of residential dwellings respectively). This paper quantifies differences in cumulative CO2 emissions by comparing early and delayed action compliance scenarios. Early versus delayed action can deliver an additional 19.5% (1.22 MtCO2eq) emissions reduction within private passenger transport and an additional 6.3% (0.76 MtCO2eq) within the residential sector, between 2021-2030. The paper also develops precedent scenarios using known diffusion rates that provide a benchmark evaluation of these climate policy targets and highlight their unprecedented scale. These precedent scenarios reach just 24% of the EV target and 47% of the residential retrofit target, which highlights the risk of focusing on end-of-period headline targets, the importance of diffusion rates and implementation pathways for policy formation. The paper addresses the need for a robust framework which can progress the policy narrative to include implementation pathways and carbon budgets, not just final year headline targets. Finally, some tailored policy recommendations are provided based on distinct innovation adopter categories.

Highlights

- Bass diffusion model combined with a GHG simulation model
- Scenario analysis of two of Ireland’s headline policy targets: EVs and retrofit
- Early action policy compliance scenarios deliver additional savings of 11%, relative to delayed action
- Projected uptake indicates policy target shortfalls of 76% for EVs and 53% for retrofitting
- Bespoke policy guidance for distinct innovation adopter categories

Keywords

Diffusion pathways; Carbon budgets; LEAP; Energy efficiency; Policy support; Policy simulation

1. Introduction

European Union (EU) climate policy distinguishes between large energy consuming installations and smaller distributed greenhouse gas emitters. The EU Emissions Trading Scheme (ETS) is the key policy instrument for reducing emissions in energy intensive industry, power/ heat generation and commercial aviation. The remaining emissions in transport, built-environment, agriculture, and waste (i.e. non-ETS emissions) are managed through effort sharing agreements amongst EU Member States. The ETS Directive 2003/87 (EU, 2003) sets out an overall emissions 'cap' at EU level (that reduces over time), provides a 'trading' mechanism and emission allowances for ETS companies. While the ETS sector has struggled to deliver the expected increasing price signal for allowances and has faced structural challenges in its implementation, it has evolved to function more effectively over time (Narassimhan et al., 2018). EU policy for reducing non-ETS emissions is articulated in the Effort Sharing Decision (ESD), Decision No 406/2009/EU (EC, 2009), in which each member state has a legally binding non-ETS target. To date, these non-ETS emissions have been challenging to reduce.

In addition to 2020 GHG emission reduction targets at member state level, the 2009 ESD included annual GHG reduction targets for the period 2013 – 2020. These annual targets - Annual Emission Allocations (AEAs) - effectively established a non-ETS carbon budget for each EU member state. Member state targets vary based primarily on relative wealth, measured by gross domestic product (GDP) per capita, and other factors. Ireland's mandatory target is to achieve at least a 20% non-ETS GHG reduction in 2020, relative to 2005 levels. Cumulative AEAs establish an effective non-ETS carbon budget of 338 $MtCO_{2eq}$ for the period 2013-2020. The responsibility for national GHG emission inventories and projections in Ireland falls to the Environmental Protection Agency (EPA). In 2020, the EPA's GHG projections report stated that Ireland is likely to achieve between 2 and 4% reduction in non-ETS GHG emissions in 2020, relative to 2005 levels (EPA, 2020). This projected carbon budget in the period 2013-2020 will be 349 $MtCO_{2eq}$, indicating a shortfall of 11 $MtCO_{2eq}$ (EPA, 2019). Ireland has purchased some non-ETS emissions allowances and will need to purchase additional allowances to ensure compliance with the 2020 target. Only two member states, Ireland and Malta, are projected to fail to meet their 2020 non-ETS GHG targets (European Environment Agency, 2018).

For 2030, non-ETS GHG emission targets are specified under the Effort Sharing Regulation (ESR) (EC, 2016). Ireland's current 2030 target is to reduce GHG emissions by 30%, relative to 2005 levels. Based on annual targets from 2021 the non-ETS carbon budget for the period 2021-2030 is 378 $MtCO_{2eq}$. Given the shortfall in achieving 2020 emission reductions, there is a knock-on effect to 2030 targets that will require additional policy measures. The EPA is required to produce a range of emission projection scenarios as part of the EU Monitoring Mechanism Regulation (MMR) (EU, 2013). The MMR requires each member state reports emissions projections in two scenarios, a 'with existing measures' (WEM) and 'with additional measures' (WAM). The most recent EPA projections estimate a carbon budget deficit of 51 $MtCO_{2eq}$ for the period 2021 – 2030, and a surplus of 8.9 $MtCO_{2eq}$ in the WEM and WAM scenarios, respectively. The 2030 targets are due to be increased, in line with the EU's increased ambition for 2030 (to achieve a 55% rather than 40% reduction in total GHG emissions by 2030 relative to 1990 levels).

This paper introduces a new modelling tool, LEAP Ireland GHG, developed using the Low Emissions Analysis Platform (LEAP) modelling platform. The model is used to undertake scenario analysis on two key policy ambitions in Ireland's Climate Action Plan: rapid diffusion of electric vehicles and significant deep retrofitting of residential buildings. The paper quantifies the cumulative emissions savings associated with early versus delayed action implementation of these key climate policies. The modelling is underpinned by analysis of two adopter categories (early market actor and mainstream market actor), which given the distinct behaviours of these two groups, enables insights into tailored policy formation. The market actors are simulated using the Bass diffusion model which describes the diffusion process of new products as the interaction between users and potential users (Bass, 1963). A more complete review of the Bass model formula and methodology is provided in section 3.1.

Ireland is an interesting case study as many of the policy challenges faced are applicable to other member states, including challenges with reducing non-ETS emissions with heat and transport. Additional challenges include a relatively high GHG emissions share from agriculture, a relatively dispersed settlement pattern and relatively high car dependency. This study uses a robust framework to highlight the importance of implementation pathways and cumulative emission savings to achieve final year headline targets.

Section 2 provides the policy context for this analysis. Section 3 discusses the methodology, presenting the LEAP Ireland GHG model. Section 3 also constructs the scenarios to explore the impact on GHG emissions of early or delayed target compliance for the period 2021 – 2030. There is a focus on the diffusion of electric vehicles within private passenger transportation and the retrofitting of existing dwellings. Section 4 presents the results and section 5 draws conclusions and highlights some of the policy implications.

1 Background

1.1 Policy Context

Ireland has produced multiple policy documents during the period 2013-2020. Notably the National Develop Plan (NDP) (DPER, 2018) and the more recent Climate Action Plan (CAP) (Government of Ireland, 2019). These policy documents outline measures across all sectors of the economy, i.e. transport, residential, services, industry, power generation and agriculture. Table 1 outlines some of the headline policy targets, relevant to this study, outlined within the NDP-2018 and CAP-2019 indicating the year of implementation and sub-sectoral area. This analysis explores two key areas of policy priority in Ireland, addressing the introduction of electric vehicles (EV) within private passenger transport and residential retrofitting.

Policy	*Sector*	*Sub-sector*	*Target*	*Description*
NDP-2018	Transport	Private Passenger Transport	500,000 EVs	Deliver 500,000 electric vehicles by 2030, inc. additional charging infrastructure
			Non-zero Emissions Vehicle ban	No new non-zero emission vehicles sold post 2030
	Residential	Existing Dwellings	45,000 Dwellings p.a.	Retrofit 45,000 dwellings per annum to minimum 'B' standard (<= 125kWh/m^2.annum)
CAP-2019	Transport	Private Passenger Transport	840,000 EVs	Deliver 840,000 electric vehicles by 2030, inc. additional charging infrastructure
			Non-zero emission ban	No new non-zero emission vehicles sold post 2030
	Residential	Existing Dwellings	500,000 Dwellings (inc. 400,000 Heat Pumps)	Deliver 500,000 residential retrofits to minimum B2 standard (<= 100 kWh/m^2.annum) and install at least 400,000 electric heat pumps

Table 1 - National Development Plan and Climate Action Plan residential retrofitting and private passenger transport targets

Ireland's more recent CAP-2019 committed to a significant increase in the number of EVs, specifically a shift from 500,000 to 840,000 EVs in private car transport by 2030. Nomenclature is important in the context of EV policy discussion as the percentage share of these overall targets being delivered by Plugin-Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV) has also changed over time. The CAP-2019 target consists of 35% PHEV (290,000) and 65% BEV (550,000) whereas the 500,000 NDP target consisted of 75% BEV's.

1.1.1 Progress to date

Assessing progress to date with respect to EV penetration and retrofitting activity requires an understanding of the evolving nature of the targets. With respect to EV diffusion, Ireland has witnessed a significant gap between policy targets and delivered results. In 2008, a 2020 EV target of 10% of all vehicles was established, translating into approximately 230,000 EVs by 2020 (DCENR, 2009, p. 1). In 2014, this was revised downward to a total of 50,000 EV's by 2020 (DCENR, 2014, p. 3). By 2019 there were approximately 9,481 BEV/ PHEVs on Irish roads (SIMI, 2019). Figure 1 shows the historic number of registered BEV and PHEV vehicles on Irish roads, highlighting the 2020 target of 50,000 EVs by 2020 and the need for 41,519 EV sales in 2020 to reach the target.

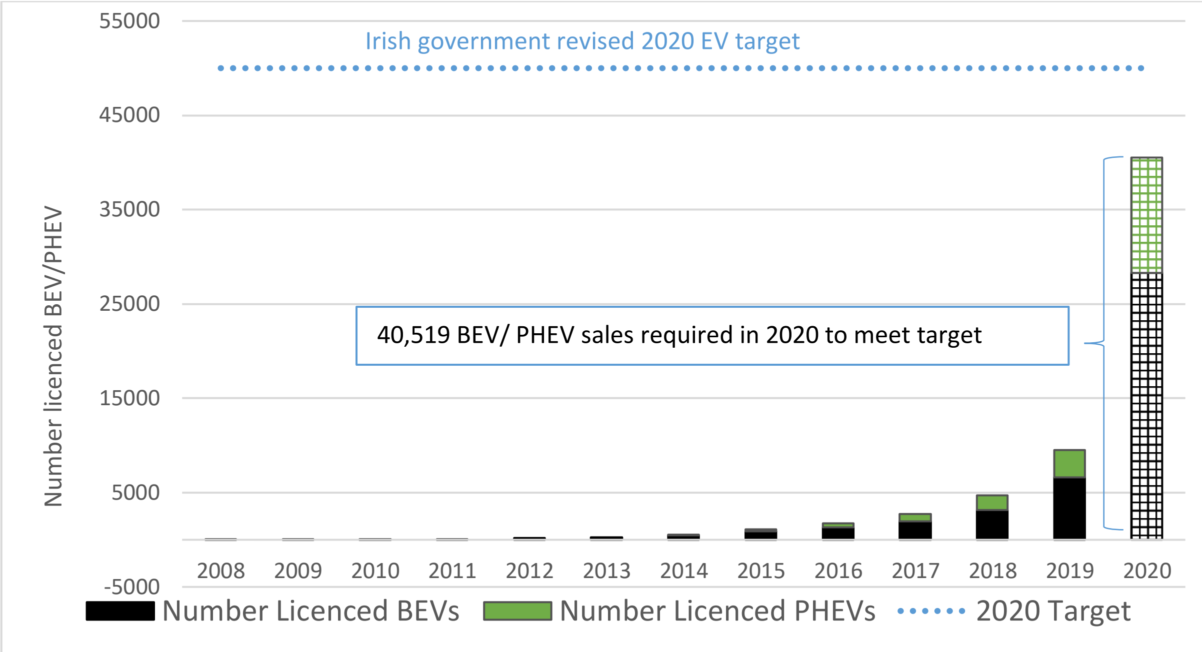

Figure 1 - Historic number of BEV/ PHEV vehicles

Retrofitting uptake activity and depth has also been slower than expected. Retrofit depth can be broadly categorised as shallow/ deep retrofit. A shallow retrofit typically consists of discrete building fabric upgrades which focus on a limited number of retrofit measures, achieving limited energy efficiency improvements. Conversely a deep retrofit focuses on achieving much deeper levels of energy efficiency improvements by applying an integrated retrofit strategy which considers the effect of a combination of retrofit measures. The proposed 2030 targets have shifted over time; the NDP-2018 policy specifies approximately 405,000 dwelling retrofits during the period 2018 – 2027 (to a minimum standard of at least 125kWh/m^2/annum). The CAP-2019 policy increases this target, aiming to deliver 500,000 residential retrofits by 2030 (to a minimum standard of at least 100 kWh/m^2/annum), including 400,000 heat pumps delivered to existing dwellings. At present, Ireland is completing approximately 23,000 residential retrofits per annum (Government of Ireland, 2019), the majority of which are shallow retrofits. Retrofit grant schemes in Ireland have the potential to deliver significantly greater energy efficiency improvements than previously witnessed (Mac Uidhir et al., 2019). Between 2017-2020, 526 residential dwellings received grant support to achieve deep retrofits, as part of the Sustainable Energy Authority of Ireland's (SEAI) Pilot Deep Retrofit Grant (PDRG), achieving an energy efficiency rating of at least 75 kWh/m^2/annum (SEAI, 2019). Figure 2 shows the current rate of shallow/ deep retrofits, with current trends projected to 2030, relative to the 2030 CAP-2019 retrofit target. Shallow retrofit activity does not typically reach the stated levels of energy efficiency improvement required in the target and accounting for shallow retrofit activity, the target is missed by 176,000 retrofits by 2030. Deep retrofits account for approximately 1841 of all retrofits by 2030 at this current rate, representing just 0.6% of all projected future retrofit activity.

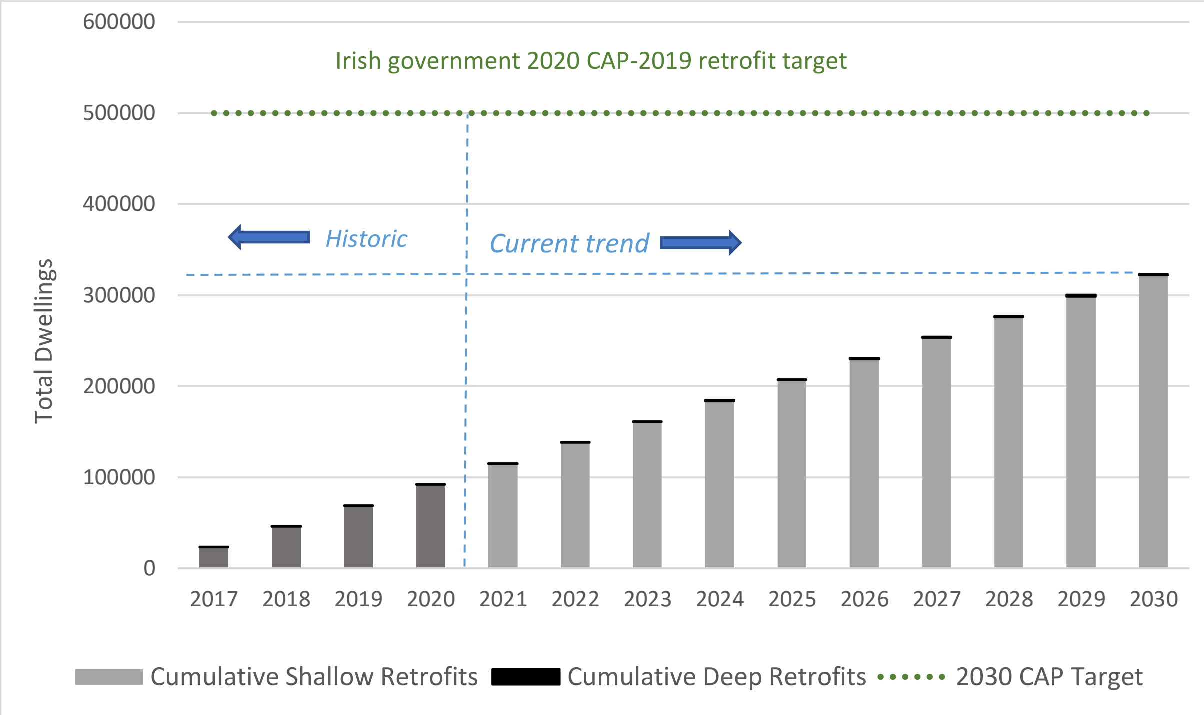

Figure 2 - Historic and projected cumulative shallow/ deep dwelling retrofits (2017 - 2030)

2.1.2 Potential difficulties with delivering targets

The progress to date highlights the scale of the task with respect to achieving more ambitious 2030 targets. The CAP-2019 policies recognise the need to improve the supply chain in delivering deeper retrofits at scale, however does not consider the potential supply constraint difficulties associated with delivering the unprecedented number of EV's required by 2030 (Olivetti et al., 2017, McKinsey, 2018). Additionally, current policy does not provide clarity on what type of vehicles will be displaced and what homes will be retrofitted. O'Neill et al (2019) highlight additional difficulties associated with the large scale importing of diesel vehicles from the UK and the lack of clear policy for the future of diesel vehicles post 2030. A key policy difficulty with respect to large scale deployment of EVs lies within the interdependence of the required national charging infrastructure and personal user incentive to switch to an EV. There is a need to provide an evidence-base on which to formulate robust policy which adequately considers the wide range of mitigation outcomes associated with delivering climate policies. By considering the implications of the carbon budget approach between 2021 and 2030, this study explores the number and type of vehicles and dwellings which will be displaced/ retrofitted in each year. An essential component in delivering all the benefits associated with these ambitious 2030 targets requires that the policies also adequately consider the delivery pathways.

1.2 Diffusion of innovations

The theory of diffusion of innovation explores the rate at which innovations are adopted across a range of adopter categories and innovation characteristics. Rogers categorises five adopter types (innovators, early adopters, early majority, late majority, and laggards) and a range of innovation characteristic (relative advantage, compatibility, complexity, trialability and observability). A five-stage “innovation-decision” process is described as: 1) knowledge, 2) persuasion, 3) decision, 4) implementation and 5) confirmation (Rogers, 2003) with each stage representing a step in the decision-making process from initial awareness of an innovation to final adoption and implementation.

The theory has been supported and modified by multiple empirical studies. Analysis by Franceschinis et al (2017) of household preference for ambient heating technologies finds evidence to support the diffusion of innovation theory, while aggregating the five adopter categories into three categories: early, late-majority and late adoption characteristics. Simpson and Clifton (2017) confirm the presence of early-majority diffusion characteristics with respect to financial incentives and the adoption of residential solar heating in Australia, highlighting the difficulties associated with crossing the “chasm” between early-adopters, who typically prioritise environmental and technological concerns, and the early-majority, who typically prioritise financial concerns, in the context of diffusion (Moore and McKenna, 2014). Noel et al. explore the concept of “conspicuous diffusion”, in which the theory of conspicuous consumption (Veblen and Galbraith, 1973) is combined with Roger’s diffusion theory to gain insight into the impact which status and perception play on diffusion of electric vehicles in broader society. Noel et al. show that the diffusion of electric vehicles in the Nordic region follows the theory of conspicuous diffusion particularly well, concluding that the successful conspicuousness of EVs (Tesla, Nissan) has stimulated the adoption of the technology amongst innovators, maximised the technological distinction within society, and stimulated peer-to-peer status “emulation” as the adoption creates a new social norm and enters the early-adopter market. Additionally, this process encouraged other manufactures (VW, BMW) to begin conspicuous diffusion and promote further technology choice.

Many aspects of the theory of diffusion have received widespread recognition, e.g. technological diffusion tends to follow an S-shape curve, the total number of potential adopters’ changes over time and changes within the internal evolution of the innovation affects overall diffusion. These diffusion characteristics highlight the need to view diffusion as an on-going and evolving process with respect to the diffusion of any specific innovation (Kemp and Volpi, 2008). As already noted, the different adopter categories are sometimes aggregated depending on the level of data available. These different adopter categories can be used to provide tailored policy recommendations, since what works as a policy measure for one group (e.g. early adopters) might not work for a different group (e.g. late majority). Based on the literature, an overview of some of these differences is given in Table 2.

	Early market actors	Mainstream market actors
Socio-Economic Status	More likely to be wealthier	Less likely to be wealthier
Motivation	Environmental concerns; future opportunities; driven by initiative	Cost of product being economical; reaction to a need for compliance
Information	High level of knowledge; active searcher for information; relies on diverse sources of information	Knowledge restricted to standard products; passive recipient of information
Peer influence	Not strongly influenced by peers; confident in own judgement	Actively influenced by peers; external authority carries weight
Risk	Risk-taking; sees risks as manageable	Risk averse; avoids risks & uncertainty where possible
Solution preferences	Unique, bespoke, different	Standard solutions preferred
Benefits	Perceive benefits strongly	Good enough is sufficient
Behaviour	Leads; contrarian	Follows; conformist

Table 2 - (source, adapted from Wilson et al, 2017 & Edmond et al, 2006)

2.2.1 Policy instruments and diffusion

In an analysis of housing associations in the Netherlands (Egmond et al., 2006) use two aggregated adopter categories of early market (innovators and early adopters) and mainstream market (early and late majority) to develop a set of tailored policy instruments for improving building energy efficiency at a quicker rate than previously. They define four main categories of policy instruments: (1) judicial, (2) economic, (3) communicative, and (4) structural.

Judicial instruments create a legal requirement to abide by regulations such as new building regulation standards or the certification of the energy performance of a building. These instruments tend to focus on the introduction of new minimum standards and serve less value in addressing the replacement of less energy efficient technologies which are already in use.

Economic instruments can be either positive or negative. Positive economic instruments such as financial subsidies risk the free-rider effect, whereby early-adopters who would otherwise have adopted an innovation benefit from reduced cost, with less impact on the late adopter categories. Negative economic instruments, such as levies and taxation based on energy efficiency can be effective at influencing late adopter categories, but only if this adopter type is informed.

Communicative instruments can go beyond the simple conveyance of information and serve to reduce cost and uncertainty while simultaneously improving societal awareness and acceptance of a new technology/ measure, bridging the gap between early adopters (who may participate in informational and demonstration schemes) and the late-majority/ mainstream market groups.

Physical provisions such as district heating schemes have the potential to influence late adopter categories as they represent less risk through instilled cooperation and adoption of a technology at scale. To give one example of an insight arising from combining adopter categories and policy instruments: the authors point out that given that early-market actors are often highly motivated, financial incentives are less effective for this group, whereas they are effective for mainstream-market actors.

2 Methodology

The methodology has six -parts: (1) The identification of key 2030 policy measures, (2) The use of Diffusion Rates which deliver identified targets, (3) LEAP simulation modelling to quantify emissions reductions associated with each diffusion scenario, (4) Scenario analysis and comparison, (5) Quantification of cumulative emissions savings, and (6) Policy implications and impact on adopter categories. Each section is described in detail while Figure 3 outlines each step within the methodology.

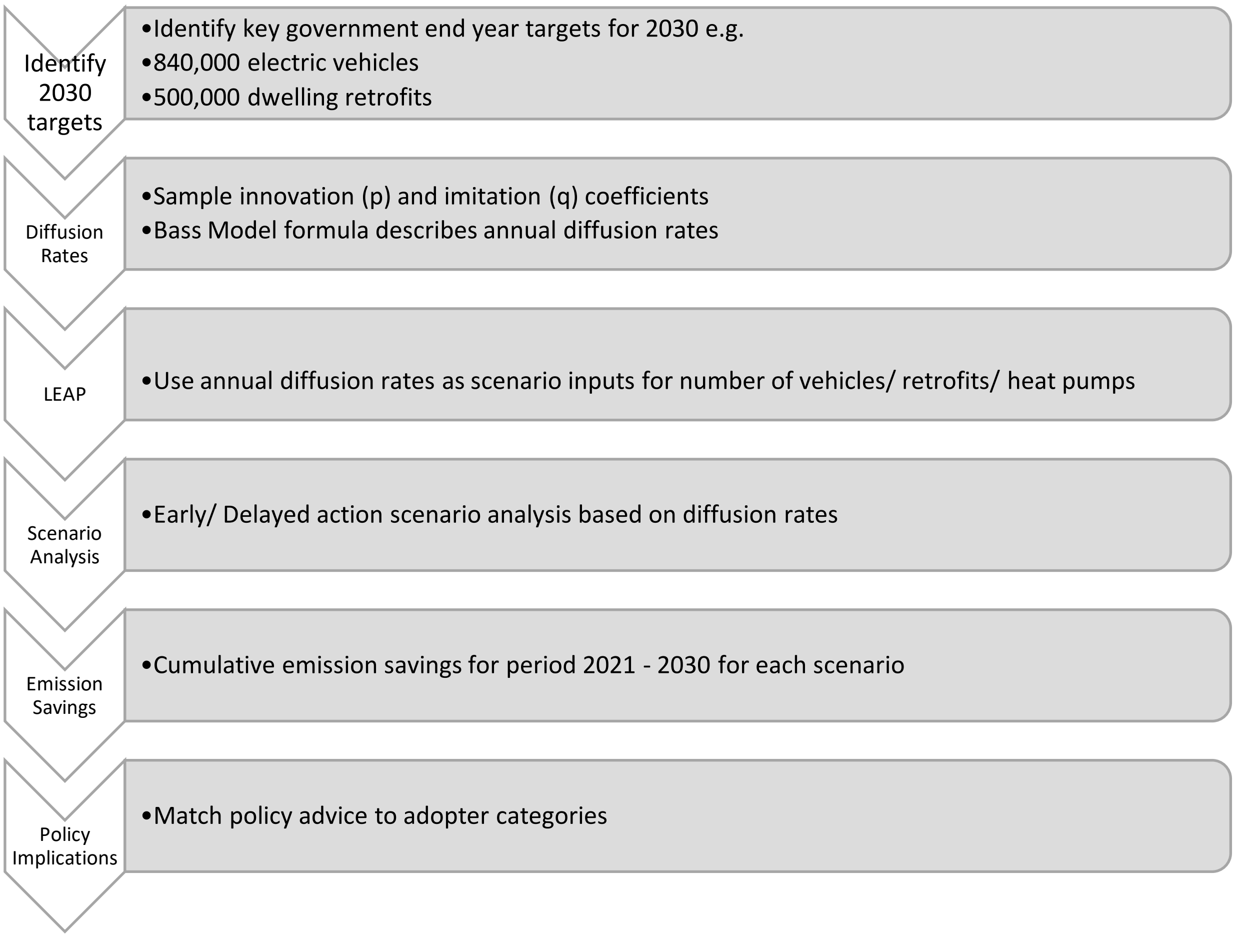

Figure 3 - Policy implementation pathway - Methodological flowchart

3.1 Diffusion Rates

In a simplification of Rogers adopter categories, Bass (1963) describes the process of how new products get adopted as an interaction between *users* and *potential users*. The Bass model formula (Equation 1) describes diffusion of innovation as a function of innovation (p) and imitation (q) variables within the potential market (M) (Bass, 1969). The coefficient of innovation (p) is not dependent on the number of prior adoptions and is therefore considered an external influence on market diffusion. However, the coefficient of imitation (q) is proportionally linked to the number of cumulative adoptions over time (A(t)). The Bass model formula utilises these coefficients to amalgamate adopter categories, providing a simplified mathematical description of complex diffusion rates, which facilitates scenario analysis.

$$\frac{f(t)}{1-\frac{A(t)}{M}} = p + \frac{q}{M}.[A(t)]$$

Equation 1 – Bass Model formula

f(t) = rate of change of installed base fraction

M = the potential market (ultimate number of adopters)

p = coefficient of innovation

q = coefficient of imitation

A(t) = cumulative adopter function

It is inherently difficult to forecast future rates of innovation and imitation within the Bass equation as they are usually specific to the innovation being considered and require at least four historic periods to estimate. In the absence of historic values, it is possible to utilise p, q values for a similar innovation to those being studied. Comparative analyses of similar innovation diffusion trends are required to provide insights into the potential success and implementation pathways for Ireland.

A number of studies have examined the market diffusion of electric vehicles in multiple regions (Fojcik and Proff, 2014; Gnann et al., 2018, 2015; Jensen et al., 2016), including estimates of imitation and innovation coefficients. However, less is known about the potential for large scale market penetration of residential retrofitting. Schleich, 2019 analysis of the adoption of high, medium, and low cost energy efficient technologies for 15,000 households across 8 EU countries concludes that regional comparisons based on a single “harmonized methodology” are lacking. Sandberg et al., 2016 analysis of 11 EU countries highlights that while EU energy efficiency building policy presents increasingly ambitious “renovation rates”, it rarely evaluates the “likeliness of reaching these rates”. Rosenow and Galvin, 2013 evaluate energy efficiency programmes in Germany and the UK, finding that disparities exist in the programme formulation to account for the difference between modelled versus measured energy efficiency savings achievable from a retrofit programme.

This paper uses a previous study of the market diffusion of EVs within Norway (Jensen et al., 2016; Massiani and Gohs, 2015) as a benchmark for Ireland’s potential for EV diffusion. Norway was chosen as a case study because its market penetration of EVs has been relatively successful (IEA, 2019). For residential retrofitting, no such alternative region was identified which could serve the same benchmarking function. Therefore the work of (Collins and Curtis, 2017a, 2017b, 2016) on residential retrofitting in Ireland was used. This analysis on retrofit take-up, depth and abandonment rates was used to develop benchmark diffusion rates. In their investigation of the potential diffusion coefficients for residential energy efficiency renovations, Curtis et al. identify adoption of retrofit measures is likely to be consistent with the classical theories of Two-Step Flow of Communication and Rogers' Diffusion of Innovation theory. The precedent scenario for residential retrofitting focuses on the impact of advertising and investment spill over on diffusion, referred to here as the AdInS scenario.

Mahajan et al., 1995 provide an overview of generalisations for p and q values, indicating an average p value of 0.03 and average q value of 0.38. However Jeuland, 1994 notes that the value of p is often quite small, less than 0.01 and q is rarely smaller than 0.3 or greater than 0.5. When p = 0 the Bass model S-curve reduces to a logistic distribution and when q = 0 the model reduces to an exponential curve. The generalised figures are summarised in Table 3.

Study	*p-value*	*q-value*	*S-curve response*
Mahajan et al.	0.03 (average)	0.38 (average)	Regular
Jeuland et al.	p > 0.01 (often)	0.3 < q < 0.5 (often)	Regular
-	0	NA	Logistic
-	NA	0	Exponential

Table 3 - Bass model innovation (p) and imitation (q) generalised coefficients

The exploratory p and q values for each scenario are shown in Table 4 and described in detail in section 3.3. Compared to the average p and q values as found in the literature, our policy scenario p and q values are quite low; however, compared to the precent scenarios we develop, our policy scenario p and q values are quite high. It is also worth noting that the profile of our delayed action scenario p and q values (i.e. p < q) is similar to the literature cited average values.

Scenario	***p***	***q***
Reference values (from literature)	0.01-0.03	0.3-0.5
CAP EV Early_action	0.023	0.21
CAP EV Delayed_action	0.010	0.34
EV Norway	0.002	0.23
CAP Retrofit Early_action	0.021	0.14
CAP Retrofit Delayed_action	0.015	0.20
Retrofit AdInS	0.013	0.06

Table 4 - Innovation (p) and Imitation (q) coefficients by scenario

This paper identifies potential p, q values which deliver end-year targets over a period of analysis. It is an accepted practice to utilise similar historic technology diffusion rates to provide an initial estimate of potential p, q values for an analogous technology (Jensen et al., 2016; Lilien et al., 2000; Radojičić and Marković, 2009). This study is not primarily an assessment of implementation pathway feasibility, but instead provides an approach to estimate the difference in carbon reduction potential in differing policy implementation pathways using different p, q coefficients and a simulation model (LEAP).

3.2 LEAP Ireland Model

The Low Emissions Analysis Platform (LEAP) is an integrated GHG and energy simulation modelling tool developed by the Stockholm Environmental Institution (C. G. Heaps, 2016). LEAP is a tool which is used on different spatial and temporal scales. One primary strength of LEAP lies in its capacity to conduct scenario analysis and consider the impact of specific climate policies.

This section outlines the LEAP Ireland GHG simulation model structure and scenarios. The LEAP Ireland GHG model builds on the previous work of (Rogan et al., 2014), adding additional levels of detail in the form of complex datasets for the Industry, Commercial Services, Transport, Residential and Agriculture sectors. These datasets are required to analyse national GHG mitigation strategies and allow for the inclusion of GHG emissions at a detailed subsectoral level. This paper provides a description of the model structure for the passenger transport and residential sectors of the new LEAP Ireland GHG model. A full detailed description of all model sectors has been published separately (Mac Uidhir et al., 2020).

The LEAP energy system modelling tool was identified as providing a representative platform which could incorporate the need for flexible detailed bottom-up modelling structures within transport, residential, industry, commercial services and agriculture while also including a top-down econometric structure within other subsectors, as data required.

3.2.1 LEAP transport

The private passenger transport subsector is described by various vehicles of different fuel types (Petrol, Diesel, CNG, Electric) and engine sizes (< 900cc, 901 – 1200cc, 1201 – 1500cc, 1501 – 1700cc, 1701 – 1900cc, 1901 – 2100cc, > 2100cc), for twenty-five years of vintage information between 2016 and 2030. Activity for each vehicle size is measured in vehicle kilometres (veh-kms) and final energy intensity is measured as Megajoule per kilometre (MJ/km). The model assumes EVs replace smaller internal combustion engines (ICE) first, EVs take the place of larger ICE sizes as the need to replace significant numbers of private passenger vehicles increases to 2030.

3.2.2 LEAP residential

The residential sector is described by nine unique building archetypes. These included building type: detached, terrace, apartment and energy efficiency classification, divided into three categories (low, medium, high) based on the Building Energy Rating (BER) alphabetic labelling system AB, CD and EFG. The model focuses on the retrofitting of existing dwellings and hence assumes new dwellings, post-2020, are constructed to a standard not requiring retrofitting. This implies a pool of potential dwellings which can be retrofitted over time. Activity for this sector is therefore measured by the number of each archetype dwelling and energy intensity for each archetype is measured in kWh m^{-2} $year^{-1}$. In LEAP, energy intensity within this sector is represented by an aggregated energy efficiency rating for each archetype.

3.3 Scenario Analysis

Two key areas of policy discussion in Ireland revolve around the introduction of EVs within private passenger transport and the retrofitting of residential dwellings. This paper generates a range of scenarios to simulate the GHG reductions which are technically possible due to their implementation. These scenarios use the diffusion rate figures to explore the impact of turnover rate within EVs and retrofitting.

3.3.1 EV Scenario assumptions

The feasibility of rapid diffusion of EVs raises multiple questions with respect to the development of vehicle types/choices and the required infrastructure within private passenger transport. We assume that smaller, more fuel efficient internal combustion engines (ICE) will initially be replaced by electric engines. Xing et al., 2019 utilised a discrete choice model of new vehicle demand to simulate counterfactual sales and conclude that EVs are replacing relatively fuel-efficient ICE vehicles (average fuel economy of 8.14 L/100km). As the total stock of smaller ICE vehicles is replaced, larger ICE engines are replaced with EVs in both scenarios. Table 5 provides an overview and description of each EV scenario. Both CAP scenarios (CAP EV Early action and CAP EV Delayed action) meet the 2030 target of 840,000 EVs. The EV Norway scenario utilises known diffusion rates for EVs in Norway and applies them in an Irish context. The known p, q values for Norwegian EV diffusion (Jensen et al., 2016; Massiani and Gohs, 2015) are used with the Bass formula (*Equation 1).* This provides an estimate of growth rates for EVs in Ireland which considers the smaller numbers on EVs in the base year (2016).

Scenario	Sector	Metric	2016	2030	Description
Reference	Transport	BEVs	1600	37400	Low Growth EV uptake
		PHEVs	400	23400	
CAP EV Early Action	Transport	BEVs	1600	547462	Rapid Early growth in EV uptake achieving 2030 target
		PHEVs	400	294768	
CAP EV Delayed Action	Transport	BEVs	1600	547106	Delayed Growth (2023 start) in EV uptake, achieving 2030 target
		PHEVs	400	294582	
EV Norway	Transport	BEVs	1600	145481	EV uptake proportional to Norway diffusion potential
		PHEVs	400	49190	

Table 5 - LEAP IE GHG base year/ final year EV uptake scenario assumptions

Figure 4 presents the p, q values for the early/ delayed action EV scenarios and the annual sales of new EVs for each year in the analysis period.

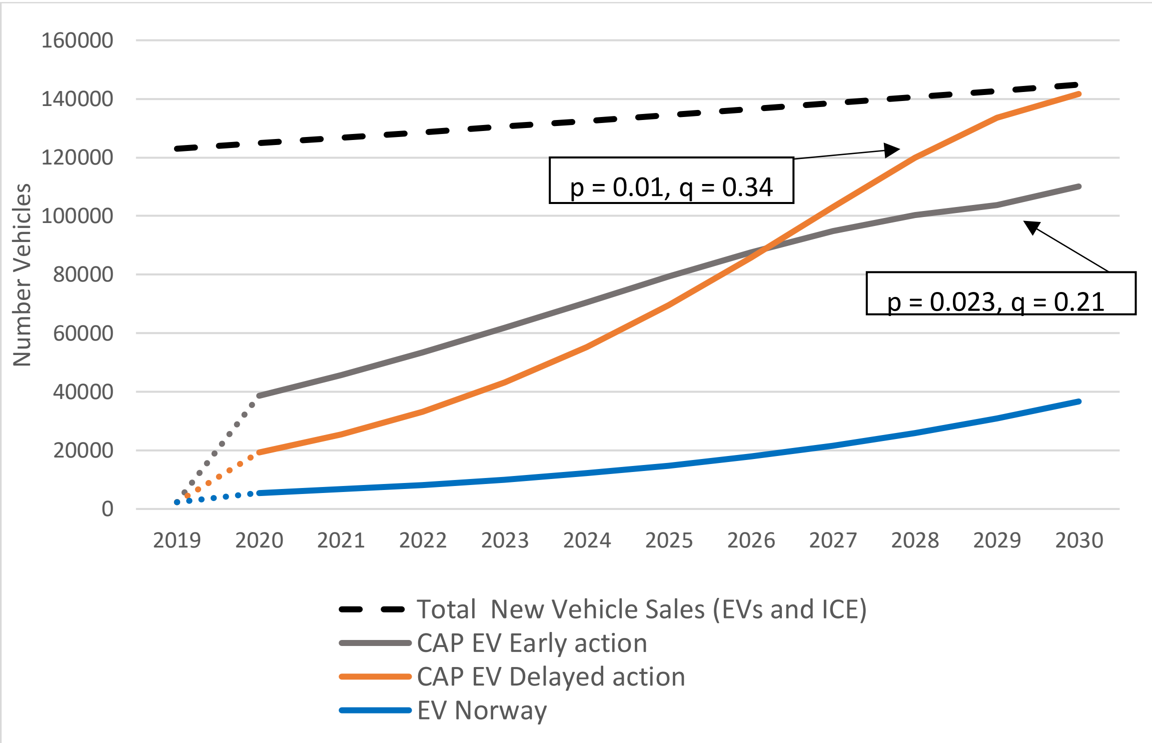

Figure 4 - Electric Vehicle Scenarios - New Sales of Electric Vehicles per annum

ICE vehicle replacement assumptions

This scenario simulates the impact of initially replacing smaller ICE vehicles (<900cc, 901cc – 1200cc, 1201cc – 1500cc) with electric vehicles. In both early/ delayed action scenarios there is a progressive increase in the vehicle engine size, reaching engine sizes of 1701 -1900cc by 2030 in the early action scenario and engine sizes greater than 2100cc in the delayed action scenario. Figure 5 and Figure 6 show the number of vehicles, by fuel type and engine size, replaced in each year between 2021 and 2030 for the early/ delayed action scenarios, respectively. Figure 7 shows the annual ICE replacement by engine size in the EV Norway scenario, not exceeding small 900 – 1200 CC petrol engines in any year as the total number of EV's introduced is reduced relative to the target compliant scenarios.

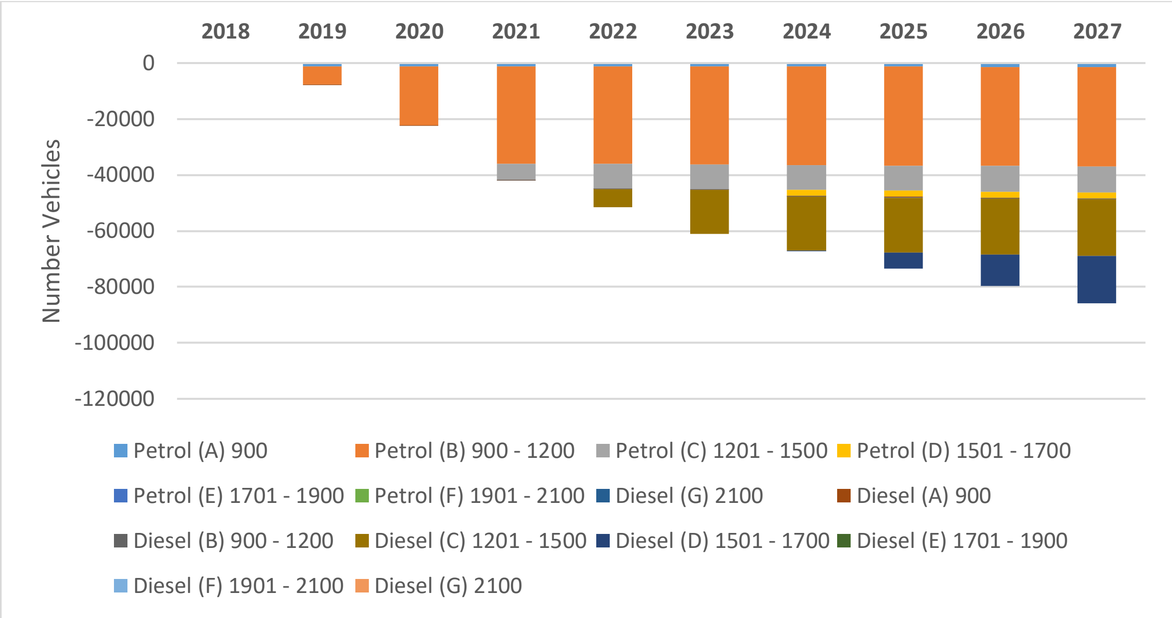

Figure 5 - ICE Vehicle displacement: CAP EV Early action scenario

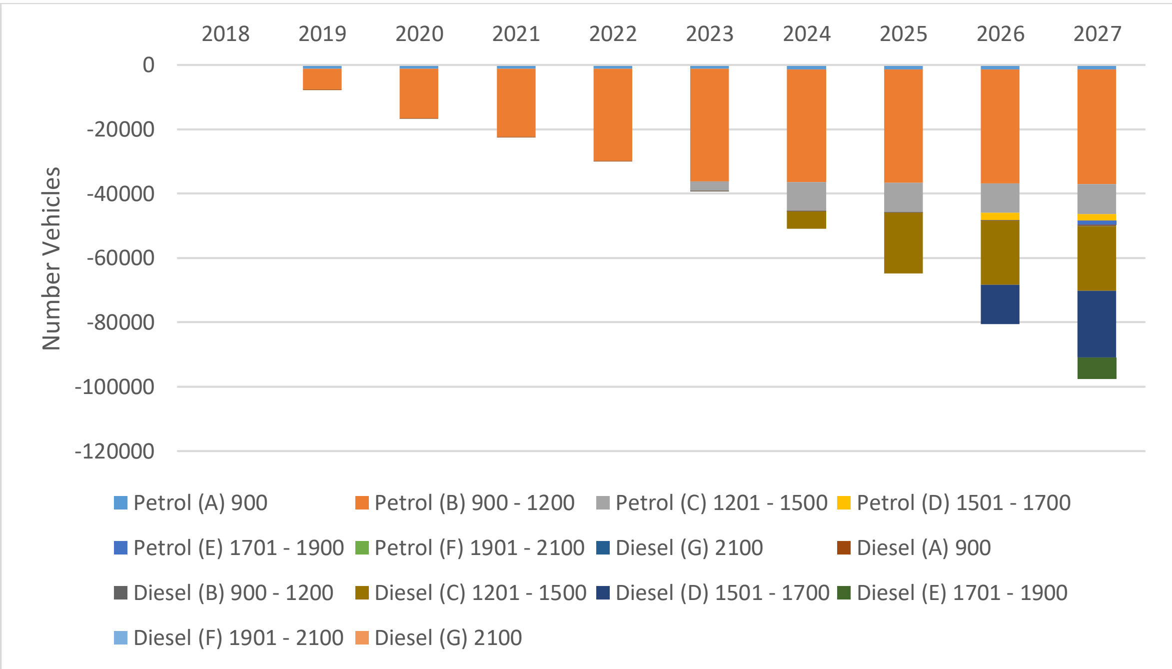

Figure 6 - ICE Vehicle displacement: CAP EV Delayed action scenario

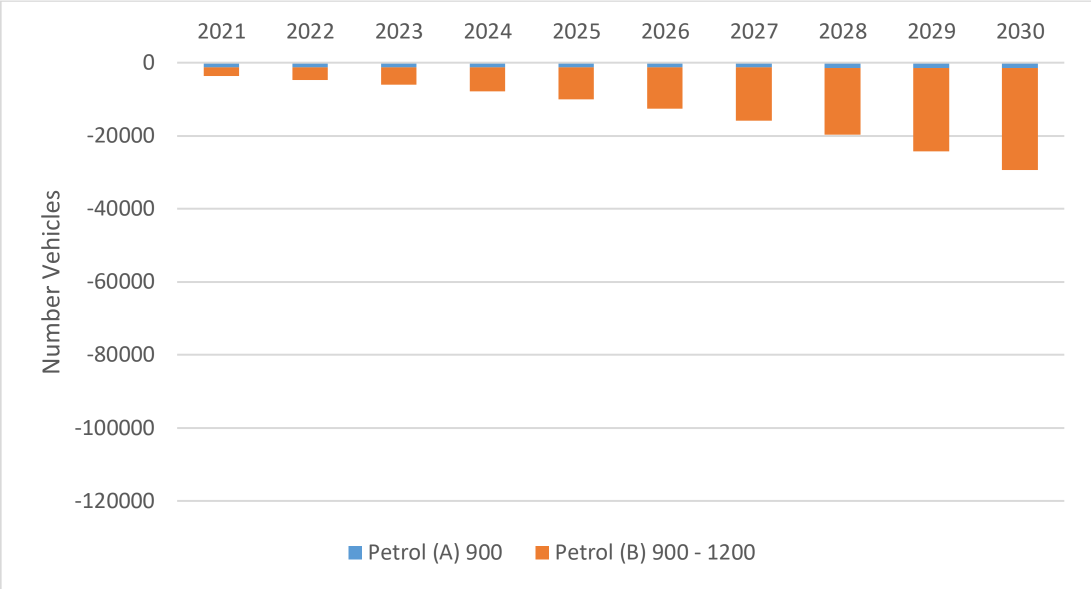

Figure 7 - ICE Vehicle displacement: EV Norway scenario

3.3.2 Residential retrofitting assumptions

Table 6 provides an overview of the number of retrofits and a description of each retrofit scenario. Both CAP scenarios (CAP Retrofit Early action and CAP Retrofit Delayed action) meet the 2030 target of 500,000 residential retrofits, including 400,000 heat pumps. The AdInS scenario utilises p and q values based on the work of Collins and Curtis (2017a), where the impact of advertising and investment spill over is explored in an Irish context.

Scenario	***Sector***	***Metric***	***2021***	***2030***	***Description***
Reference	Residential	Terraced_CD	131.5	460	Low Growth Deep retrofit uptake
		Terraced_EFG	131.5	460	
		Detached_CD	131.5	460	
		Detached_EFG	131.5	460	
CAP Retrofit Early Action	Residential	Terraced_CD	7908	15223	Rapid Early growth in Deep retrofit uptake achieving 2030 target
		Terraced_EFG	7908	15223	
		Detached_CD	7908	15223	
		Detached_EFG	7908	15223	
CAP Retrofit Delayed Action	Residential	Terraced_CD	6084	18187	Delayed Growth in Deep retrofit uptake, achieving 2030 target
		Terraced_EFG	6084	18187	
		Detached_CD	6084	18187	
		Detached_EFG	6084	18187	
AdInS Scenario	Residential	Terraced_CD	4500	6398	Retrofit uptake and diffusion potential based on (Collins and Curtis, 2017a)
		Terraced_EFG	4500	6398	
		Detached_CD	4500	6398	
		Detached_EFG	4500	6398	

Table 6 - LEAP IE Residential retrofit scenario assumptions (2021 – 2030)

Figure 8, Figure 9, and Figure 10 indicate the number and type of residential archetypes retrofitted in each period of analysis. Dwelling numbers differentiate between retrofits which include heat pumps and those which do not. For example, Terraced_CD_wHP indicates the annual number of terraced dwellings with an initial BER rating of C or D, retrofitted to a minimum standard of 100 kWh/m^2 year (B2 standard) including an electric heat pump. The p, q values indicated for each scenario dictate the diffusion rate and total number of annual dwelling retrofits. The Early and Delayed action retrofit scenarios each deliver 500,000 retrofits by 2030, while the AdInS scenario delivers 235,000 retrofits by 2030.

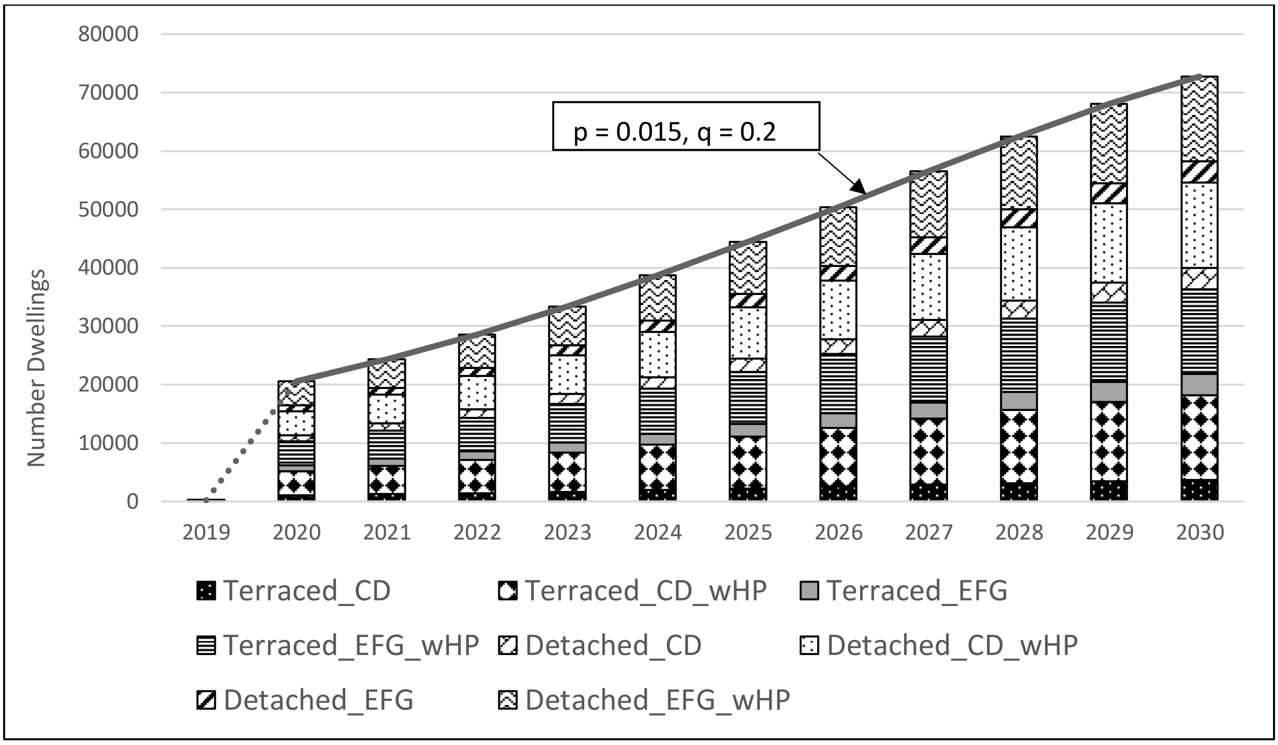

Figure 8 - CAP Retrofit Delayed action scenario; number dwellings retrofitted per annum by archetype

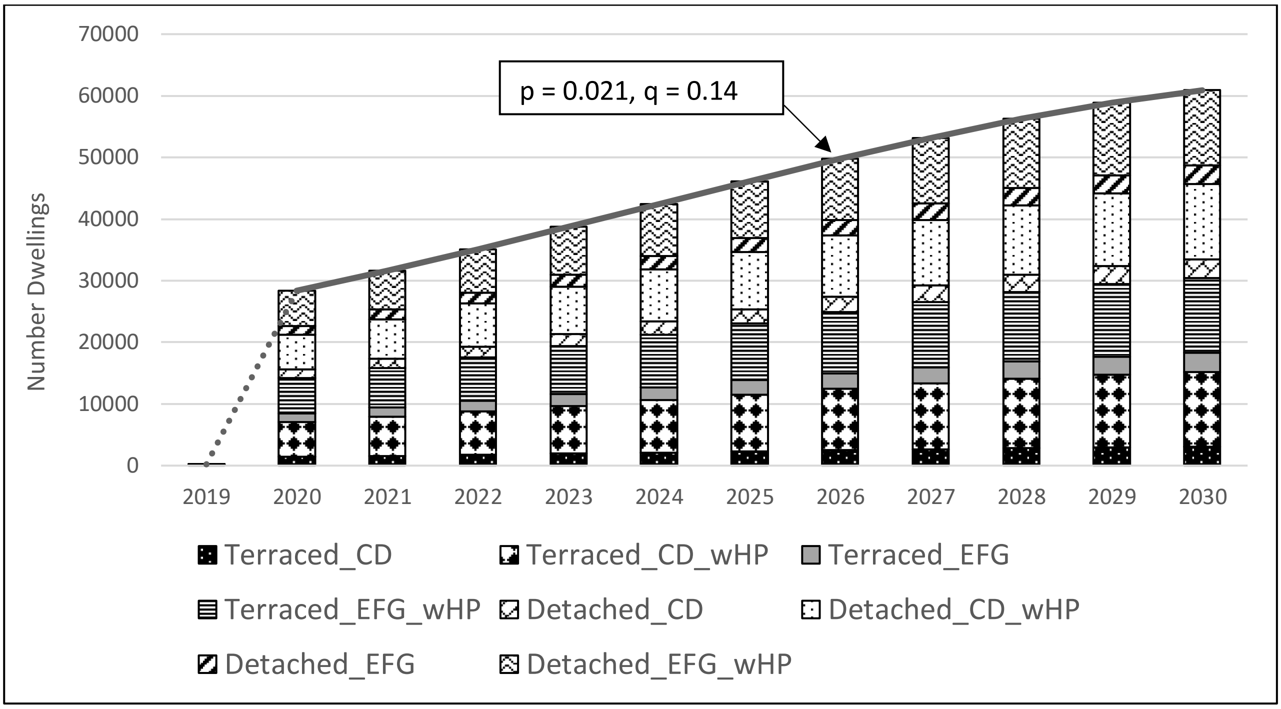

Figure 9 - CAP Retrofit Early action scenario; number dwellings retrofitted per annum by archetype

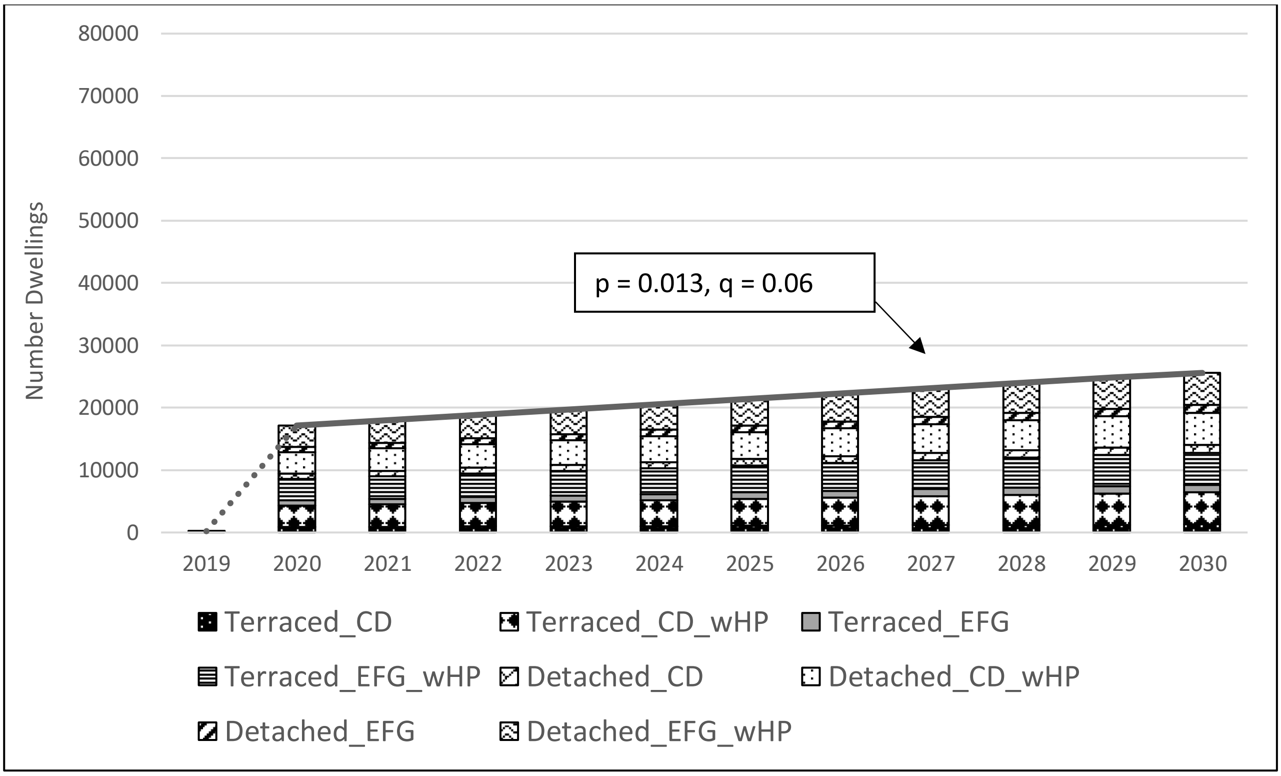

Figure 10 - AdInS scenario - number dwellings retrofitted per annum by archetype

3 Results

The results have been grouped by relevant scenarios and highlight what technologies are introduced in each year.

3.1 Private Passenger Transport – Electric Vehicles Diffusion

Each CAP compliant scenario achieves the target of 840,000 EV's by 2030. In all cases the smallest capacity engines are replaced first, in favour of battery electric vehicles and plug-in hybrid electric vehicles. The EV Norway scenario achieves a total of 200,420 EVs by 2030. Each figure also includes the 2030 EV percentage share of new vehicle sales in 2030. Figure 11 and Figure 12 show the number of EVs being added to the system in each year together with the cumulative emissions reduction. Figure 12 shows the annual EV diffusion and cumulative emissions reduction as a result of the EV Norway scenario. There is a range of emissions reductions across all scenarios;

1. 7.50 MtCO2 – CAP EV Early action, Figure 11
2. 6.28 MtCO2 – CAP EV Delayed action, Figure 12
3. 0.64 MtCO2 – EV Norway, Figure 13

Despite both CAP scenarios achieving the 840,000 EVs by 2030 target, there is a difference between early and delayed action of 1.23 MtCO2. The delayed action scenario saves 19.5% less emissions than the early action scenario. The delayed action scenario achieves approximately 10 times more emissions reduction than the EV Norway scenario.

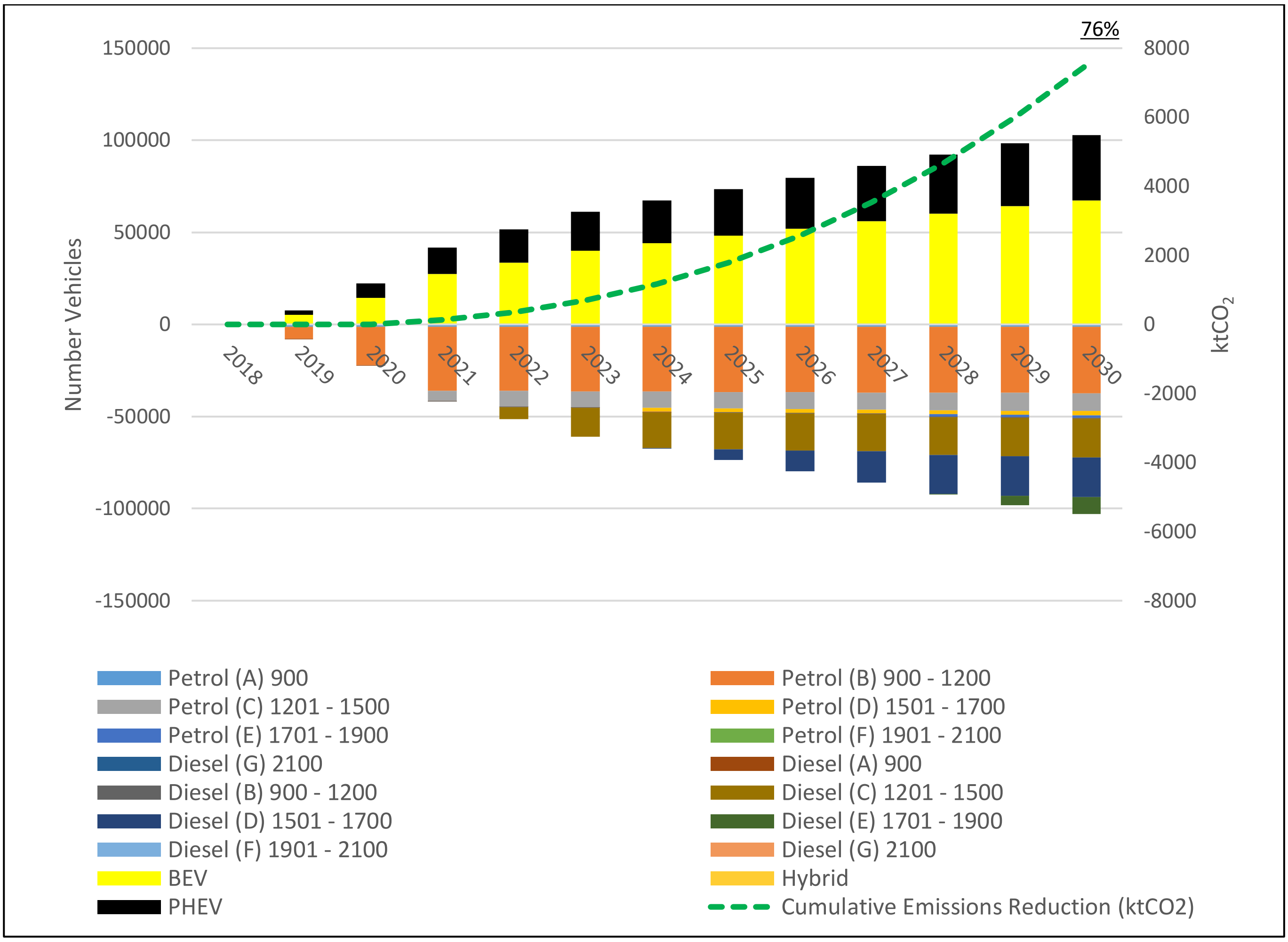

Figure 11 - CAP EV Early Action, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

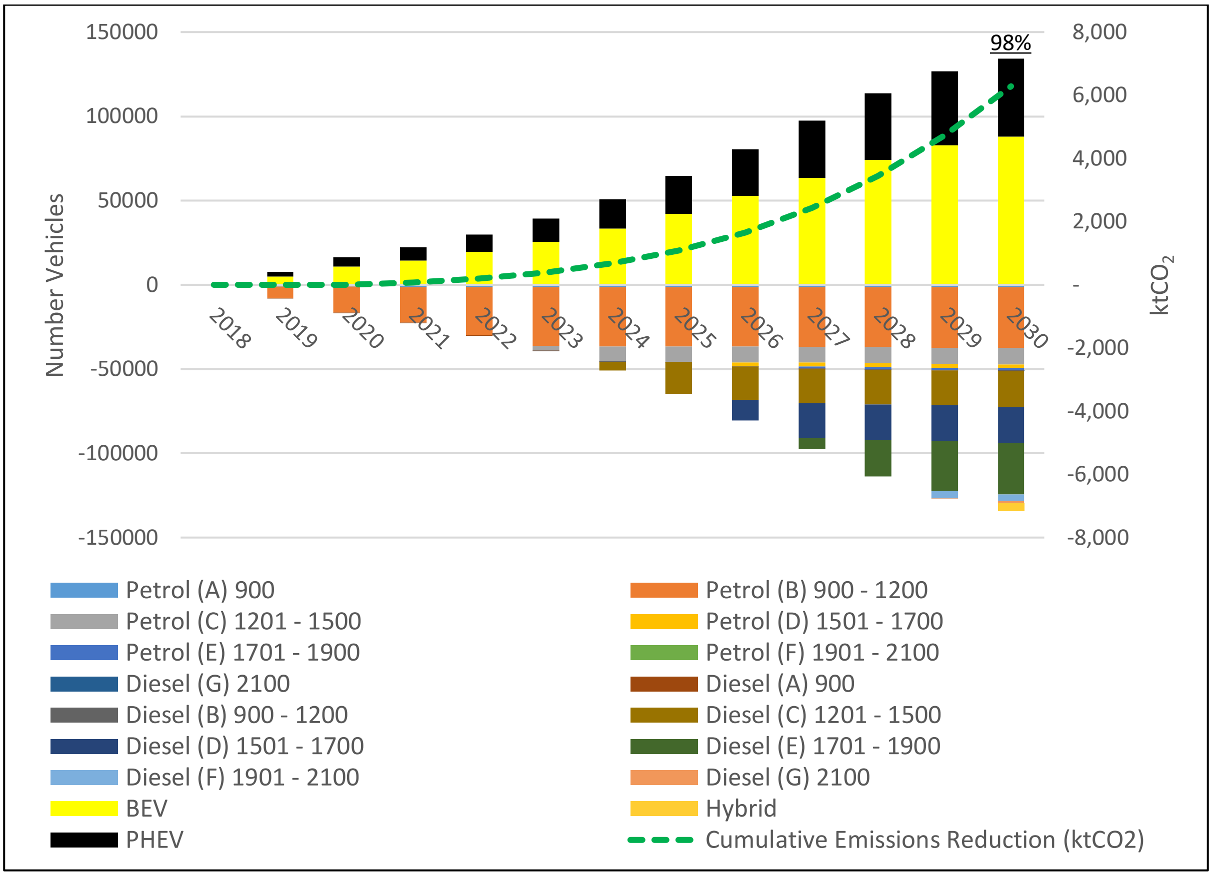

Figure 12 - CAP EV Delayed action Target Compliance, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

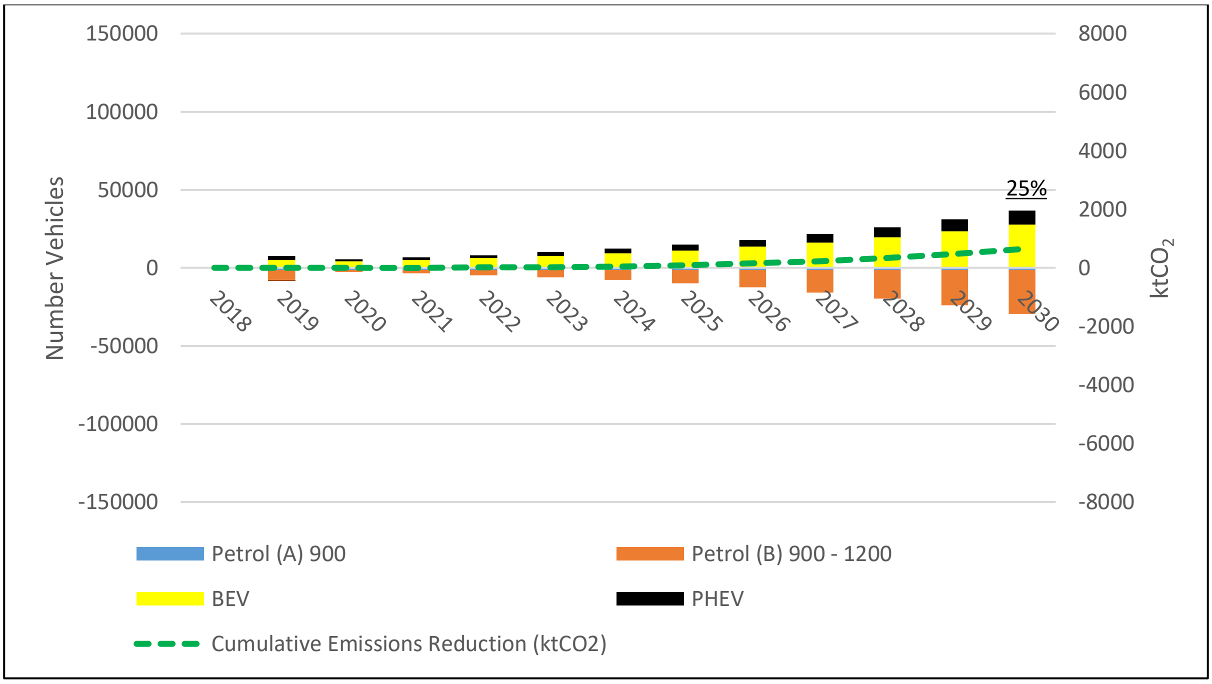

Figure 13 - EV Norway scenario, Vehicle Sales and Cumulative Emissions Reduction (ktCO2)

Regarding the engine capacity of the vehicles being removed from the system: the delayed action scenario requires a higher percentage share of total vehicles sales to be electric by 2030 (98% of all new vehicle sales), relative to the early action scenario, which rises to a higher share earlier (53% sales by 2024) but tapers out slowly to 2030, occupying a 76% share of total new car sales in 2030. The early action scenario facilitates a slower phasing out of petrol/ diesel alternatives while still delivering greater GHG emissions reductions over the period 2021 – 2030.

Section 3.3.1 provides details on the ICE vehicles being replaced in each scenario. Vehicles are indicated by fuel type and engine size for each year in the period of analysis. Table 7 indicates the number of BEV/ PHEV introduced within each scenario, for several simulation years.

Scenario	Technology	2020	2022	2024	2026	2028	2030
Early Action Target Compliance	BEV	16226	35748	46632	55275	63976	71560
	PHEV	8737	19289	25038	29753	34449	38532
Delayed Action Target Compliance	BEV	12482	21603	35902	55821	77897	92129
	PHEV	6740	11702	19342	30026	41901	49541
CAP EV Norway	BEV	4105	6144	9133	13432	19448	27520
	PHEV	1368	2048	3044	4477	6483	9173

Table 7 - BEV and PHEV stock change by scenario

4.2 Residential Dwellings – retrofitting and heat pump installation

Each scenario described for the residential sector achieves the CAP target of 500,000 dwelling retrofits, including the installation of 400,000 heat pumps. Each scenario assumes retrofits are completed evenly across terraced and detached dwellings of both EFG and CD pre-works energy efficiency standard. The variable is the rate at which the dwellings are retrofitted, see section 3.3.2 for details. Figure 14 and Figure 15 show the total emissions reduction for the analysis period 2021 to 2030 for the early and delayed action scenarios, respectively. There is a range of cumulative emissions reductions across each scenario:

1. 12.8 MtCO2 – CAP Retrofit Early action – Figure 14
2. 12.0 MtCO2 – CAP Retrofit Delayed action – Figure 15
3. 4.0 MtCO2 – Retrofit AdInS Scenario – Figure 16

There is a difference between the CAP Retrofit Early/ Delayed action emissions reduction: this additional 0.8 MtCO2eq represents an additional 6.3% reduction, relative to the least ambitious, target compliant, implementation pathway.

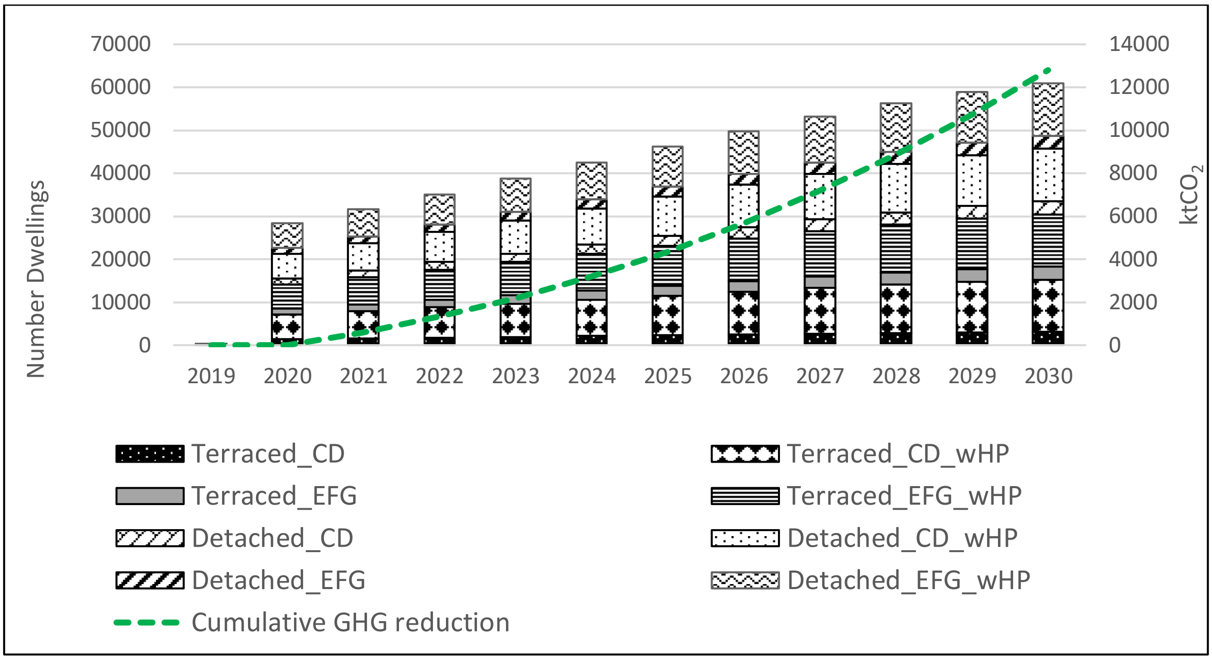

Figure 14 - CAP Retrofit Early action, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

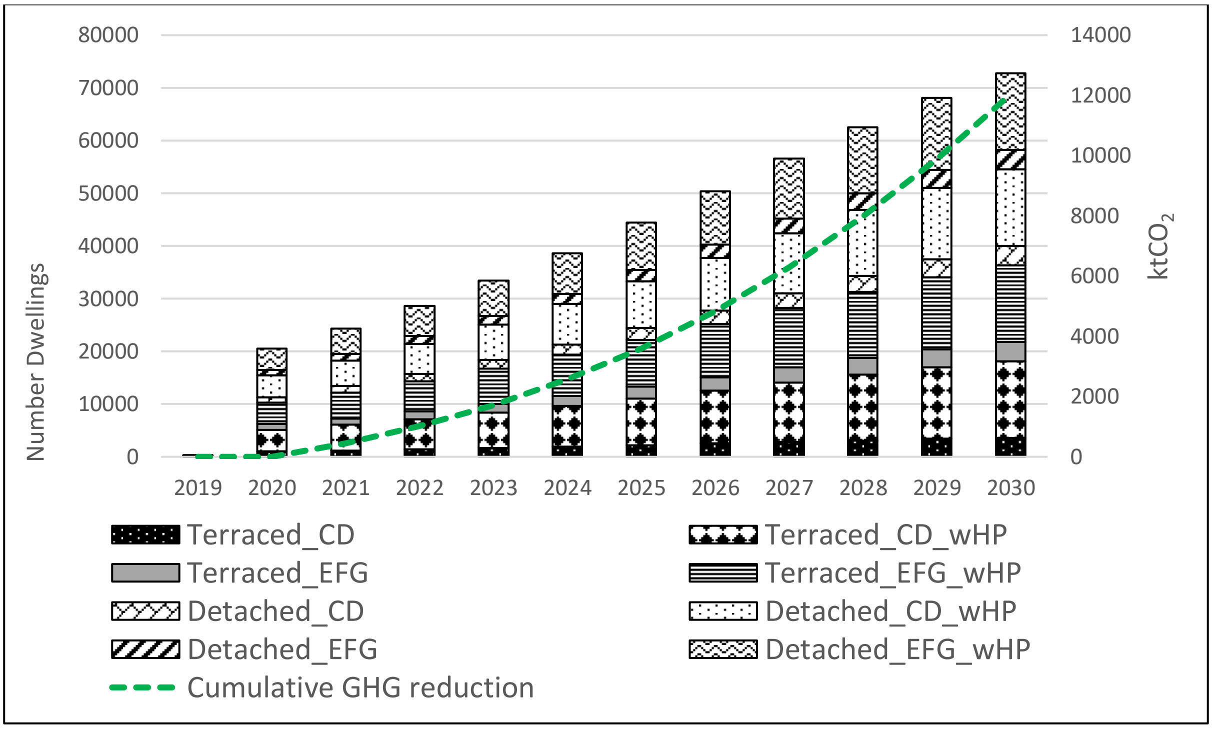

Figure 15 - CAP Retrofit Delayed action, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

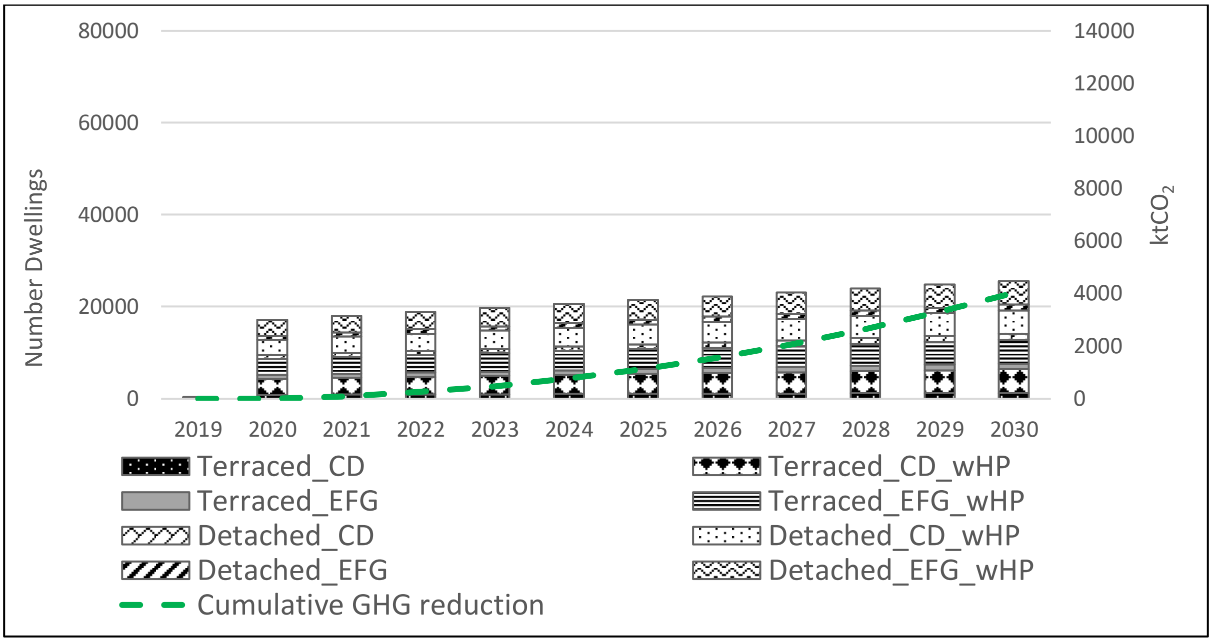

Figure 16 - AdInS Scenario, dwelling archetype retrofits and Cumulative Emissions Reduction (ktCO2)

Figure 16 shows the cumulative emissions reduction associated with the retrofit AdInS scenario, equating to 4 MtCO2 eq cumulative emissions reduction by 2030.

4 Conclusions & Policy Implications

In this paper we introduce a novel use of the Bass diffusion model, in conjunction with a new greenhouse gas emissions model for Ireland. We show the relevance of this multi-model approach by simulating two key policy goals for the period 2021-2030. The primary results of these pathways are shown in Figures 11 – 16. We argue that diffusion pathways and associated adopter categories illustrate four key insights.

First, implementation pathways matter for cumulative emissions savings and serve as a vital complement to end-year targets. The use of diffusion pathways with a bottom-up simulation model provides detailed insights into the steps required to realise targets e.g. which cars or homes are replaced or retrofitted in each year. Additionally, it aids monitoring progress to targets, improving implementation accountability and bridging the gap between current progress and future targets, providing a means to quantifiably assess aspirational policy targets.

Second, the quantification of early action shows it is possible to achieve 6 – 19% additional emission savings, relative to delayed action, in these scenarios. The results show that the most ambitious, CAP compliant, EV diffusion scenario can deliver an additional 1.23 $MtCO_{2\ eq}$. Regarding retrofitting, an additional 0.8 MtCO2eq reduction can be achieved through early adoption. Additionally, beyond the potential improved CO_2 reductions, early action facilitates a slower phasing out of incumbent technologies, enabling more continuity in the shift away from petrol/ diesel alternatives over the period 2021 – 2030. For EVs, there is a need to significantly scale-up their percentage share of new vehicle sales immediately. The early adoption rate means that the scenario requires less EV penetration in later years, requiring 76% share of new vehicle sales by 2030 – relative to a 98% share of new vehicle sales in the late adoption scenario. For retrofitting, early adoption means the total number of retrofits does not exceed 61,000 per annum – relative to 72,000 per annum by 2030 in the late adoption scenario. Given the scale of the challenge to deliver these ambitious targets, the early introduction, coupled with a less disruptive transition, will reduce the pressure on the relatively new markets and place less strain on target delivery overall.

Third, the results of the precedent scenarios highlight the scale of the challenge and the unprecedented diffusion required to meet the 2030 targets. For EVs, effort which surpasses that of the most successful EV diffusion examples would be required to deliver CAP EV targets. The EV Norway scenario delivers 200,420 EVs (23.8% of CAP target), reaching a 25% share of new vehicle sales by 2030. The retrofitting scenario that delivers 235,000 deep retrofits (47% of CAP target) is at a scale that is substantially higher than has been achieved to date.

Fourth, the differences between early market and mainstream market actors have consequences for appropriate policy design and the feasibility of achieving targets. The introduction of diffusion rates and adopter categories provides a mechanism to tailor policy formation to the specific characteristics of these target actor categories.
For EVs, early adopters are less motivated by financial incentives, which unfortunately means there are likely to be many free riders who benefitted from grant subsidies among the current cohort of EV owners. There are multiple policy implications as we seek to normalise the adoption EVs and gain access to mainstream market actors, who are typically more influenced by financial incentives. Recent EV policy discourse has mentioned that the current grant subsidy scheme has a limited lifetime. Given the policy target of increased EV penetration, and the potential for less financial incentives, this presents a challenge for finding an effective policy mix which encourages widespread adoption of the new technology. Additionally, mainstream market actors are influenced by peers and external sources of authority, therefore endorsement by influential figures and the introduction of policies to actively manage the phase out of petrol and diesel incumbents is likely to be consequential.

For deep retrofitting, the limited data relating to early adopters presents a policy challenge, as it is likely many free riders exist within the 325 homes which participated in PDRG during the period 2017 – 2019. Additionally, as the average energy efficiency achieved as part of the PDRG is significantly greater (≤ 75 kWh/m^2/year) than that expected within the current CAP target (≤ 100 kWh/m^2/year), it is difficult to expect a similar policy to function as a useful means of moving beyond innovators and accessing early adopters. Given that mainstream market actors are more sensitive to price, the financial contribution from the State will have to (as a minimum) sustain or (in order to achieve higher diffusion) possibly grow, to support the continued roll-out of deep retrofits. As information campaigns are unlikely to motivate change among mainstream actors, a need for regulations as part of the policy mix for retrofitting should to be considered. Additionally, the preference among mainstream market actors is for standard solutions. Given the normally bespoke nature of retrofitting, this will be an enormous challenge for large scale uptake. Widespread retrofitting of homes is unlikely to happen until large-scale peer-to-peer examples displace the perception of retrofitting as a costly and disruptive event with limited benefits.

In theory, policies achieve maximum benefits because of early action. In practice, policymakers contend with a broad range of concerns regarding which policies to prioritise. Future work within residential retrofitting could consider the additional co-benefits of prioritising the least energy efficient dwellings. Future analysis within the transport sector could include the impact of modal shift within private passenger transport as ever increasing shares of EV penetration present a simplified solution to the decarbonisation of transport and ignores other important areas of concern such as congestion, equitable access to mobility, and the broader health benefits associated with cleaner air. This study and associated methodology can support the decision-making process and aid in policy prioritisation and resource allocation. While the authors acknowledge that the key assumptions and diffusion rates are exploratory, the analysis provides a pragmatic perspective on the implicit diffusion rates associated with existing end year targets.

Acknowledgements

The authors acknowledge the funding and support provided by the Environmental Protection Agency (EPA - 1016-CCPR-MS.24), the SFI MaREI Centre for Climate, Energy and Marine (MaREI - 12/RC/2303) and the Climate and Energy Modelling Services to the Technical Research and Modelling (TRAM Group: ServicesRFT2016/01213/12806), and the Energy Policy Research Centre at the Economic and Social Research Institute.

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FUNDED BY:
Ireland's European Structural and Investment Funds Programmes 2014-2020
Co-funded by the Irish Government and the European Union
European Union
European Regional Development Fund
Science Foundation Ireland
For what's next