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Achieving the unprecedented: Modelling diffusion pathways for ambitious climate policy targets

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ABSTRACT

Ireland has some very bold targets, as part of a substantial overall greenhouse gas emissions reduction ambition. It is unclear however to what extent these targets are consistent with the pace at which new technologies can enter the market and become widely adopted. This paper grapples with this by combining well-respected and empirically validated estimates of technology diffusion together with energy models. Its purpose is to illuminate some of Ireland's challenges associated with meeting these targets. The results show Ireland's electric vehicle and residential retrofitting goals would require rates of technology diffusion that are well beyond the historical rates internationally of even the most successful transformations to date. This result calls Ireland's ambitions into question. Drawing on the theory of technology diffusion, the paper also provides insights into additional complementary policies that Ireland might consider in order to accelerate diffusion of key technologies. The paper demonstrates the means and the value of drawing on historical precedents to help determine the feasibility of future transition scenarios. It also points to how industry-standard diffusion theory can help to identify policy solutions to accelerate the energy transition.

1. Introduction

The EU Effort Sharing Decision (ESD) is the key policy instrument for reducing emissions in transport and the built-environment, Decision No 406/2009/EU [13]. Each member state has legally binding targets, established as Annual Emissions Allocations (AEA) for the period 2013 – 2020. These AEAs - establish an effective carbon budget of 338 $MtCO_{2eq}$ for Ireland up to 2020 with a target to reduce emissions by 20%, relative to 2005 levels. Ireland achieved a reduction of 7% by 2020 [15]. For 2030, GHG emissions for transport and the built-environment are specified under the Effort Sharing Regulation (ESR) [12]. Ireland's current 2030 target is to reduce GHG emissions by 30%, relative to 2005 levels. Based on AEAs this establishes a carbon budget of 378 $MtCO_{2eq}$ for the period 2021–2030. The 2020 shortfall has an impact on the 2030 targets. The most recent EPA projections estimate a range of possible outcomes including a deficit of 51 $MtCO_{2eq}$or a surplus of 8.9 $MtCO_{2eq}$ for the period 2021 – 2030.

This paper explores two key policy targets in Ireland's Climate Action Plan [20]: rapid diffusion of electric vehicles and significant deep retrofitting of residential buildings. The paper quantifies the cumulative emissions savings associated with policy compliant scenarios that deliver government targets, and precedent scenarios which provide a benchmark to evaluate the likelihood of delivering the same. 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 [2]. The practice of benchmarking scenario diffusion rates against historical precedent has already been established. Wilson et al. [47] examine the future growth trajectories of a range of end-use technologies, including vehicles, noting that observed historic growth can provide useful insight into future diffusion. Iyer et al. [23] examine the institutional, behavioural, and social factors which affect the historic diffusion of low-carbon technologies, stating that delayed policy action results in the need for

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more rapid low-carbon technology diffusion to avoid infeasibilities in an Integrated Assessment Model (IAM). Grubler et al. [21] examine the characterisation of energy transitions and the diffusion of new technologies, noting that there is a large range in the expected diffusion speed (e.g., 2 – 50 years) dependant on upfront costs, profitability of adoption, and sector characteristics.

This paper employs a combination of the Bass diffusion model and a simulation modelling platform, the Low Emissions Analysis platform (LEAP). The use of this type of Bass diffusion modelling lies in its strong theoretical/ empirical foundation which underpins the growth in new technologies, in place of arbitrary, ad hoc scenarios often associated with energy system models. This modelling method allows for quantifiable and replicable technology diffusion scenarios in a simulation model. This method facilitates a realistic comparison between different regions when estimating the possible outcomes of distant policy targets. A more complete review of the Bass model formula and methodology used is provided in Section 3.

Section 2 provides the policy context for this analysis. Section 3 discusses the methodology, scenario assumptions and presents the LEAP model for Ireland (LEAP Ireland GHG). Section 4 presents results. Section 5 concludes and provides policy insights.

2. Background

2.1. Policy context

Ireland has produced multiple climate policy documents during the period 2013–2020. Notably the National Develop Plan (NDP) [11] and the more recent Climate Action Plan (CAP) [20]. 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, sub-sectoral area, and progress to date. Ireland's ambition with respect to electric vehicles has changed significantly over time. In 2008, a 2020 EV target of 10% of all vehicles was established (representing 230,000 EVs) ([10], p. 1). In 2014, this was revised downward to a total of 50,000 EV's by 2020 ([9], p. 3). A target of 500,000 EVs by 2030 was established in 2018 and more recently, CAP-2019 committed to a significant increase 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. Retrofit targets have also changed significantly in recent years, in 2018, a target of 405,000 retrofits (minimum standard of at least 125 kWh/m^2/annum) was established for the period 2018 – 2027. In 2019, this figure was revised upwards to 500,000 retrofits (minimum standard of at least 100 kWh/m^2/annum) by 2030. To date, 526 deep retrofits have been completed (minimum standard of at least 75 kWh/m^2/annum) as part of the Sustainable Energy Authority of Ireland's (SEAI) Pilot Deep Retrofit Grant (PDRG). In the 3 year period since this increased ambition was announced and with less than 9 years until 2030, the gap to target is widening.

2.1.1. Potential difficulties with delivering targets

While CAP-2019 policies recognise the need to improve the supply chain in delivering deeper retrofits at scale, it does not consider the potential supply constraint difficulties associated with delivering the unprecedented number of EV's required by 2030 [31, 35]. 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. [36] 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.

2.2. Diffusion of innovations

Roger's theory of diffusion categorises five adopter types : innovators, early adopters, early majority, late majority, and laggards. A five-stage "innovation-decision" process is described as: 1) knowledge, 2) persuasion, 3) decision, 4) implementation and 5) confirmation [40], 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. [17] aggregating these five adopter categories into three: early, late-majority and late adopter. Simpson and Clifton [45] highlight the difficulties associated with crossing the "chasm" between early-adopters, who prioritise environmental and technological concerns, and the early-majority, who prioritise financial concerns, in the context of diffusion [32]. Noel et al. [33] explore the concept of *conspicuous diffusion*, in which the theory of conspicuous consumption [46] 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. confirm that the diffusion of EVs in the Nordic region follows the theory of conspicuous diffusion particularly well, resulting in the adoption of EVs amongst innovators, maximising the technological distinction within society, and stimulating peer-to-peer status "emulation" as increased adoption drives a new social norm and enters the early-adopter market. 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 [26]. Different categorisations of adopters can be used to provide tailored policy recommendations, since what works as a policy measure for one group might not work for a different group (e.g., early/late majority). Based on the literature, an

Table 1
National development plan and climate action plan residential retrofitting and private passenger transport targets.

Policy	Sector	Sub-sector	Target	Description	Progress to date (2021)
NDP-2018	Transport	Private Passenger	500,000 EVs	Deliver 500,000 electric vehicles by 2030, inc. additional charging infrastructure	See below
		Transport	Non-zero Emissions Vehicle ban	No new non-zero emission vehicles sold post 2030	No progress
	Residential	Existing Dwellings	45,000 Dwellings p.a.	Retrofit 45,000 dwellings per annum to minimum 'B' standard (<= 125 kWh/m^2.annum)	See below
CAP-2019	Transport	Private Passenger	840,000 EVs	Deliver 840,000 electric vehicles by 2030, inc. additional charging infrastructure	~41,000 EVs on the road to date [44].
		Transport	Non-zero emission ban	No new non-zero emission vehicles sold post 2030	No progress
	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	526 homes deep retrofitted to "A" standard. Each of these dwellings received a heat pump.

overview of some of these differences is given in Table 2.

2.2.1. Policy instruments and diffusion

Egmond et al. [14] use two aggregated adopter categories, early market (innovators and early adopters) and mainstream market (early and late majority), to develop a set of tailored policy instruments. They define four main categories of policy instruments: (1) judicial, (2) economic, (3) communicative, and (4) structural.

Judicial instruments typically introduce new minimum standards and create a legal requirement to abide by regulations such as new building regulation standards or the certification of the energy performance of a building. *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. Negative economic instruments, such as levies, and taxation can be effective at influencing late adopter categories. *Communicative instruments* can go beyond the simple conveyance of information and serve to reduce cost and uncertainty while improving societal awareness and acceptance of a new technology/ measure, bridging the gap between early adopters and the late-majority market groups. *Structural instruments* can influence late adopter categories as they represent less risk through instilled cooperation and adoption of a technology at scale e.g., district heating.

3. 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 Fig. 1 outlines each step within the methodology.

3.1. Diffusion rates

In a simplification of Rogers adopter categories, Bass [2] describes the process of how new products get adopted as an interaction between *users* and *potential users*. The Bass model formula (Equation 1) describes the rate at which technologies are adopted. The rate of adoption f(t) is expressed as a function of the coefficient of innovation (p), coefficient of imitation (q), and the proportion of people that have adopted to time t, F (t) [1]. F(t) (Equation 2) is expressed as a function of the total potential market (M), and the cumulative adopter function to time t, A(t), which reduces the pool of potential adopters over time. The coefficient of innovation (p) is not dependant 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 adoptions over time (F(t)). Therefore innovators (p) will be of greater importance early in the diffusion process but that as time elapses the importance of imitators (q) increases. The potential market (M) is the total number of potential adopters available and remains constant over time. The M value is linked with the number of adoptions over time (F(t)) which reduces the pool of potential adopters. The Bass model formula utilises these coefficients to amalgamate adopter categories, providing a simplified mathematical description of complex diffusion rates, which facilitates scenario analysis. The Bass variant of the diffusion model was chosen as it presented a form which was complex enough to describe the uptake of new technologies, and simple enough to identify equivalent p, q values required for the precedent scenarios. Use of the Bass variant also meant that detailed information was not required to utilise successive variants of the Bass model such as generalised with pricing developed by Bass, Krishan, and Jain [3], which includes decision variables such as pricing and advertising, or the "continuous repeat purchasing" variation developed by Norton and Bass [34] which deals with dynamic sales behaviour of different generations of technologies over time.

$$f(t) = (p + q.F(t))(1 - F(t))$$

Equation 1 Bass Model formula f(t) = rate of change of installed base fraction

p = coefficient of innovation

q = coefficient of imitation

F(t) = proportion of people that have adopted to time t

$$F(t) = \frac{A(t)}{M}$$

Equation 2 Bass model function: proportion of adopters by time

$A(t)$ = cumulative adopter function

M = the potential market (ultimate number of adopters)

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 [16, 18, 19, 24], including estimates of imitation and innovation coefficients. However, less is known about the potential for large scale market penetration of residential retrofitting. Schleichs [43] 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. [42] 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 [41] 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. Cao and Mokhtarian [5] provide estimates of p, q values based on calibration of annal vehicles sales in the US for the period 1993 – 2002. Park [37] also provides estimates for p, q variables based on the diffusion of Hydrogen fuel cell diffusion for Korea.

This paper uses a previous study of the market diffusion of EVs within Norway [24, 30] 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 [22]. The precedent

Table 2
Adopter type characteristics (source, adapted from [48] & [14]).

	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

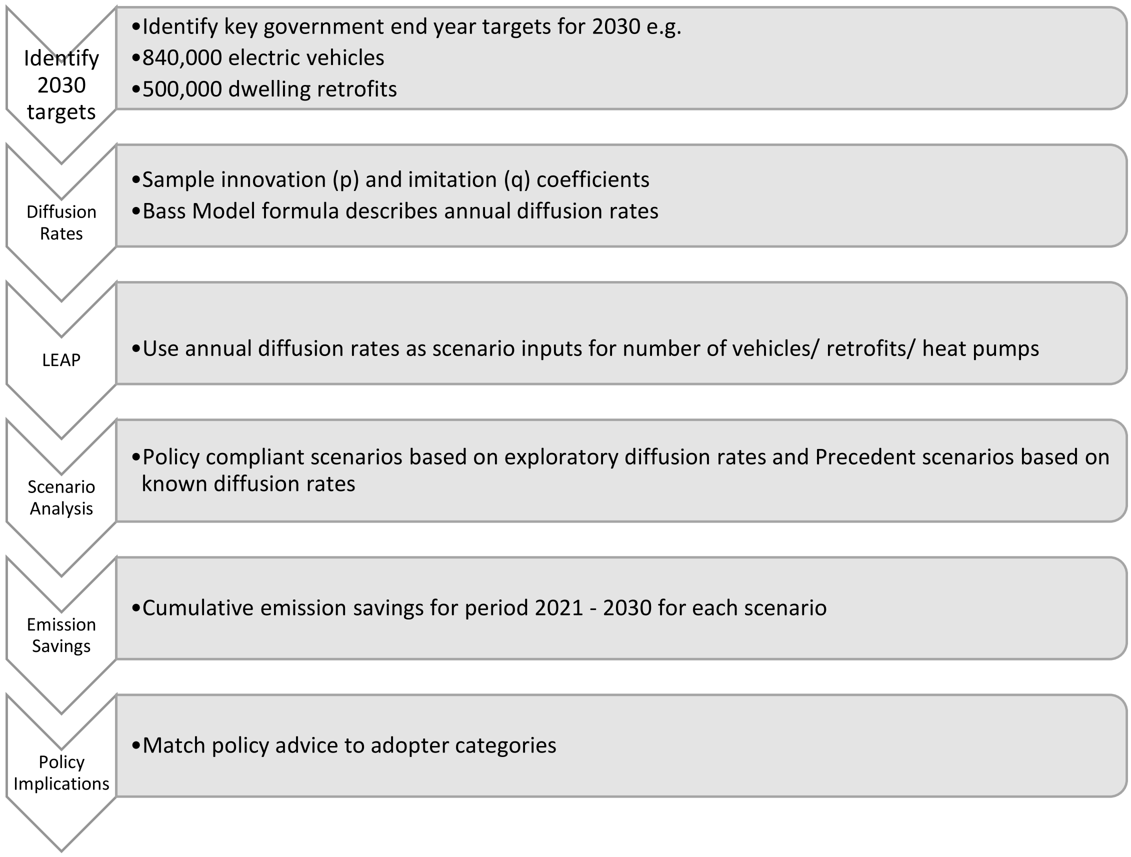

Fig. 1. Policy implementation pathway - methodological flowchart.

scenario for EVs is referred to here as the EV Norway scenario. For residential retrofitting, no such alternative region was identified which could serve the same benchmarking function. Therefore, the work of [6–8] on residential retrofitting in Ireland was used. This analysis on retrofit take-up, depth and abandonment rates was used to develop benchmark diffusion rates. Curtis et al. identify that the 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.

Typical p and q values, alongside the exploratory values used for each scenario are shown in Table 3 and described in detail in Section 3.3. There is a wide range of typical p, q values which were identified in the literature [25, 29]. Compared to the average p values found in the literature, our policy scenario p values are broadly aligned, with the exception of the EV Norway scenario, which is lower than the expected range, and closer to the p estimate presented in the work of Park et al. [37]. The scenario q values are all below the average range but broadly in line with the q value estimates presented by Cao et al. [5], and Park et al. [37], with the exception of the CAP EV compliant scenario which is in the average range.

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 [24, 27, 38]. 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 implementation pathways using different p, q coefficients and a simulation model (LEAP).

Table 3
Innovation (p) and imitation (q) coefficients by scenario.

Scenario	p	q
Reference values (from literature)	0.01–0.03	0.3–0.5
CAP EV compliant	0.01	0.34
EV Norway	0.002	0.23
CAP Retrofit compliant	0.015	0.2
Retrofit AdInS	0.013	0.06

3.2. LEAP Ireland model

The Low Emissions Analysis Platform is an integrated GHG and energy simulation modelling tool developed by the Stockholm Environmental Institution (C. G. [4]). The tool can be used on different spatial and temporal scales and provides a robust framework to conduct scenario analysis and simulation modelling. LEAP offers an inbuilt library of methods for modelling growth but does not include the Bass diffusion formula and therefore cannot utilise the necessary innovation or imitation variables by default. The LEAP Ireland GHG model builds on the previous work of [39], adding additional levels of detail in all economic sectors, allowing for the inclusion of GHG emissions at a detailed subsectoral level. A full detailed description of all model sectors has been published separately [28].

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).

3.2.2. LEAP residential

The residential sector is described by nine building archetypes, defined by building type: detached, terrace, apartment and energy efficiency classification. Energy Efficiency is defined by three categories (low, medium, high) based on the Building Energy Rating (BER) alphabetic labelling system AB, CD and EFG. 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}.

3.3. Scenario analysis

3.3.1. EV scenario assumptions

The feasibility of rapid EV uptake raises questions with respect to the development of vehicle types/choices. We assume that smaller, more fuel efficient internal combustion engines (ICE) will initially be replaced by electric engines. Xing et al. [49] 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/100 km). As the total stock of smaller ICE vehicles is replaced, larger ICE engines are replaced with EVs. Table 4 provides an overview and description of each EV scenario. The CAP EV compliant scenario meets the 2030 target of 840,000 EVs. The known p, q values for Norwegian EV diffusion [24, 30] 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). Fig. 2 presents the p, q values for the policy compliant and precedent scenarios.

3.3.2. Residential retrofitting assumptions

Table 5 provides an overview of the number of retrofits and a description of each retrofit scenario. The CAP retrofit compliant scenario meets 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 [6], where the impact of advertising and investment spill over is explored in an Irish context.

Fig. 3 and *Fig. 4* indicate the number and type of residential archetypes retrofitted in each period of analysis e.g., Terraced_CD 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). The p, q values indicated for each scenario dictate the diffusion rate and total number of annual dwelling retrofits.

4. Results

4.1. Private passenger transport – electric vehicles diffusion

The CAP EV compliant scenario achieves the target of 840,000 EV's by 2030. The EV Norway scenario achieves a total of 200,000 EVs by 2030. Each figure also includes the 2030 EV percentage share of new vehicle sales in 2030. *Fig. 5* shows the number of EVs being added to the system in each year together with the cumulative emissions reduction, for the CAP EV compliant scenario. *Fig. 6* shows the annual EV diffusion and cumulative emissions reduction in the EV Norway scenario. There is a range of emissions reductions across all scenarios.

1 6.28 MtCO2 – CAP EV compliant, *Fig. 5*
2 0.64 MtCO2 – EV Norway, *Fig. 6*

There is a significant emissions savings gap between the CAP EV compliant and EV Norway scenarios. The CAP EV compliant scenario achieves approximately 10 times more emissions reduction than the EV Norway scenario, highlighting the scale of the challenge between what is practically feasible and the aspirational target.

Regarding the engine capacity of the vehicles being removed from the system: the CAP EV compliant scenario requires a 98% share of vehicles sales to be electric by 2030 whereas the EV Norway scenario achieves a 25% share of total sales in the same year.

4.2. Residential dwellings – retrofitting and heat pump installation

The CAP retrofit compliant scenario delivers 500,000 retrofits, including 400,000 heat pumps, while the AdInS scenario delivers 235,000 retrofits by 2030. 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. *Fig. 7* shows the total emissions reduction for the analysis period 2021 – 2030 for the CAP retrofit compliant scenario, delivering 12 MtCO2eq emissions savings. Fig. 8 shows the total emissions reduction for the Retrofit AdInS scenario, delivering 4 MtCO2eq emissions savings.

1 12.0 MtCO2 – CAP Retrofit compliant scenario - *Fig. 7*
2 4.0 MtCO2 – Retrofit AdInS Scenario - *Fig. 8*

There is a significant emissions savings gap between the CAP retrofit compliant and Retrofit AdInS scenarios. The CAP retrofit compliant scenario achieves 3 times more emissions reduction than the retrofit AdInS scenario, delivering an additional 8 MtCO2 savings by 2030.

5. Discussion

The use of the Bass diffusion model in conjunction with the LEAP Ireland GHG simulation model presents some benefits and limitations. The method facilitates a realistic, sensible comparison between different regions which serves to highlight the scale of the challenge associated with delivering unprecedented climate policy targets, offering insight into the type of policy interventions which could be employed to aid in their delivery. The method primarily depends on the diffusion coefficients which represent innovation (p) and imitation (q), see Equations 1 and 2. In the case of residential retrofitting this proved difficult as no clear alternative region was identified with innovation and imitation coefficients relevant to Ireland. These coefficients dictate the speed of diffusion and require identification of appropriate coefficients from similar regions or case-studies to be usefully used for comparative purposes.

The innovation (p) and imitation (q) coefficients define the diffusion pathways for the adoption of EVs and residential retrofitting, providing annual uptake rates. The LEAP Ireland GHG model then depends on these pathways to define the range of scenarios presented in this paper. The LEAP Ireland GHG model also depends on replacement logic. In the

Table 4
LEAP Ireland GHG base year/ final year EV uptake scenario assumptions.

Scenario	Sector	Variable	2016	2030	Description
Reference	Transport	BEVs	1600	37,400	Low Growth EV uptake
		PHEVs	400	23,400	
CAP EV compliant	Transport	BEVs	1600	550,000	Rapid growth in EV uptake, achieving 2030 target.
		PHEVs	400	290,000	
EV Norway	Transport	BEVs	1600	150,000	EV uptake proportional to Norway diffusion potential.
		PHEVs	400	50,000	

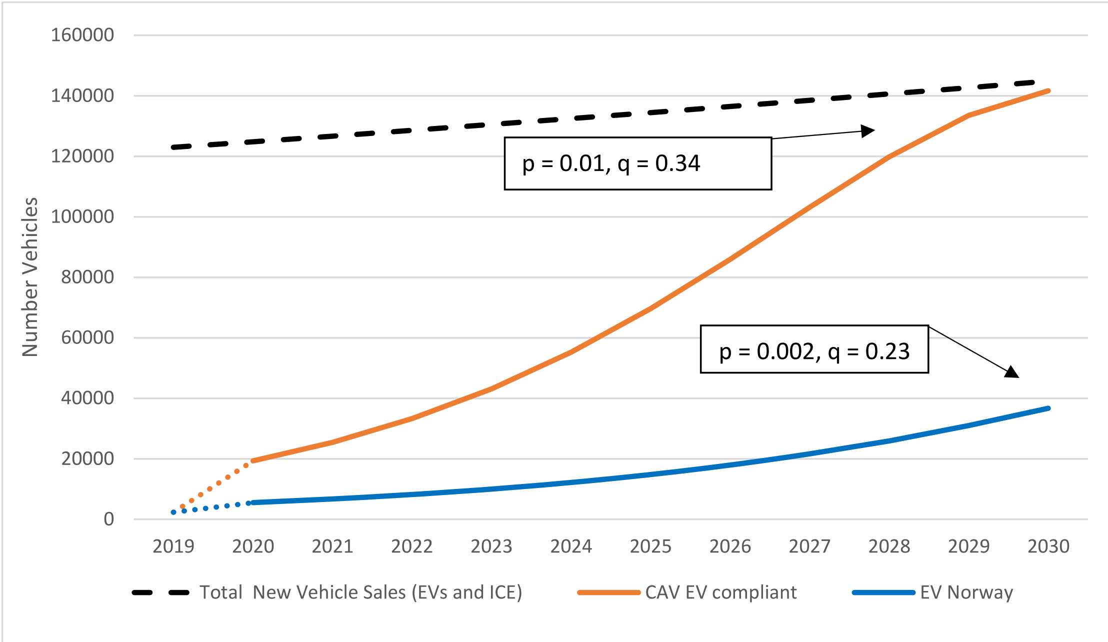

Fig. 2. Electric vehicle scenarios - new sales of electric vehicles per annum.

Table 5
LEAP IE residential retrofit scenario assumptions (2021 – 2030).

Scenario	Sector	Metric	2021	2030	Description
Reference	Residential	Terraced_CD	131.5	460	Low growth reflecting current activity.
		Terraced_EFG	131.5	460	
		Detached_CD	131.5	460	
		Detached_EFG	131.5	460	
CAP Retrofit compliant	Residential	Terraced_CD	6084	18,187	Rapid growth in deep retrofit uptake, achieving 2030 target.
		Terraced_EFG	6084	18,187	
		Detached_CD	6084	18,187	
		Detached_EFG	6084	18,187	
AdInS Scenario	Residential	Terraced_CD	4500	6398	Retrofit uptake and diffusion potential based on [6].
		Terraced_EFG	4500	6398	
		Detached_CD	4500	6398	
		Detached_EFG	4500	6398	

case of EVs, relatively fuel-efficient ICE vehicles (average fuel economy of 8.14 L/100 km) are replaced first, while for retrofitting, a mixture of energy ratings for terraced and detached dwellings are retrofitted, see Section 3.3 for details. What homes are retrofitted and what cars are replaced significantly impact on the overall emissions for each scenario and should be considered when analysing the presented results.

There is of course uncertainty surrounding the extent or scale to which the innovation and imitation coefficients presented in this paper can be achieved. Similarly, the replacement logic contains uncertainties. The scenarios presented in this paper represent a subsection of the complete range of possible outcomes and while uncertainty remains, the evidence suggests that the realised outcome will fall short of the CAP targets in 2030. Sensitivity analysis of the replacement logic could serve to address this uncertainty and the methodology could be improved by identifying a comparative case study of diffusion rates for residential retrofitting. While developing scenarios that properly capture risk and uncertainty are preferable, the ultimate objective of the analysis is not necessarily to precisely forecast technology uptake. Instead, it is to gauge the practical feasibility of policy targets substantially in advance of the target deadlines and thereby contribute to public policy discussion on the gap to climate policy targets.

6. 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. We argue that the use of a diffusion model, parameterised appropriately, is beneficial in that the focus can be on the policy outcomes as the inputs are based on a strong theoretical/empirical foundation underpinning rather arbitrary ad hoc assumptions about potential uptake rates. Diffusion models allow us to compare policy outcomes with progress made in other regions and serve to highlight potential difficulties associated with current policy targets in Ireland. The use of 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 emissions savings associated with CAP

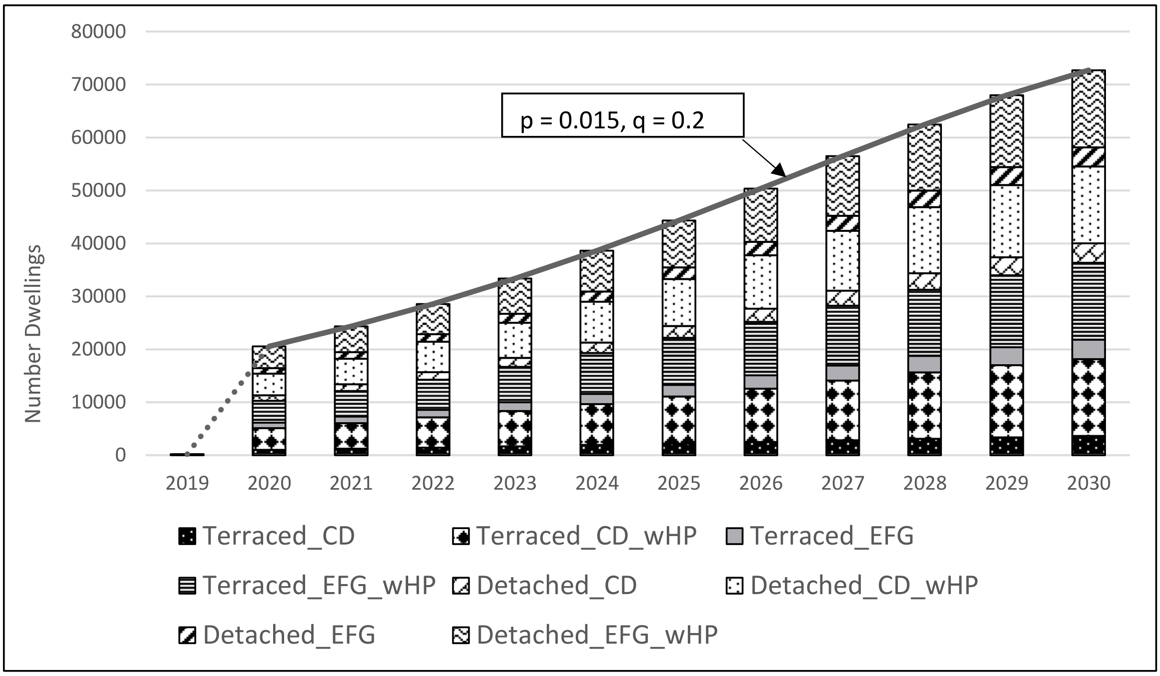

Fig. 3. CAP retrofit compliant scenario; number dwellings retrofitted per annum by archetype.

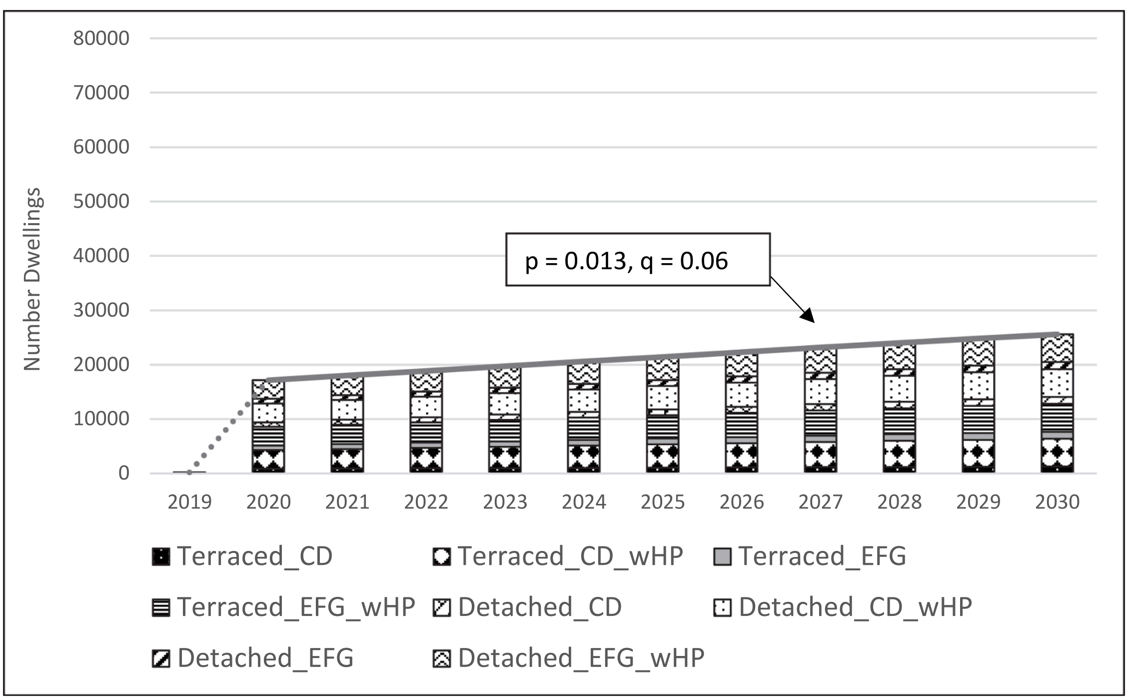

Fig. 4. AdInS scenario - number dwellings retrofitted per annum by archetype.

compliant implementation pathways shows it is possible to achieve significant emissions reductions by fully delivering the existing policy targets, approximately 18.3 MtCO2 equivalent during the period 2021 – 2030. These scenarios highlight the scale of the challenge associated with their delivery. For EVs, there is a need to significantly scale-up their percentage share of new vehicle sales immediately. Fully delivering the CAP EV compliant scenario requires a 98% share of new vehicle sales by 2030. Similarly, full delivery of the CAP retrofit compliance scenario also requires an immediate scaling-up of retrofit activity and will require 72,000 deep retrofits per annum by 2030. In both cases this level of increased activity is unprecedented and not reflected in the current market. Recent policy announcements on enhancements to retrofit schemes are a reflection that policy makers have realised that prior policy initiatives were not sufficient.

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 200,000 EVs (23% of CAP target), reaching a 25% share of new vehicle sales by 2030. The retrofitting scenario that

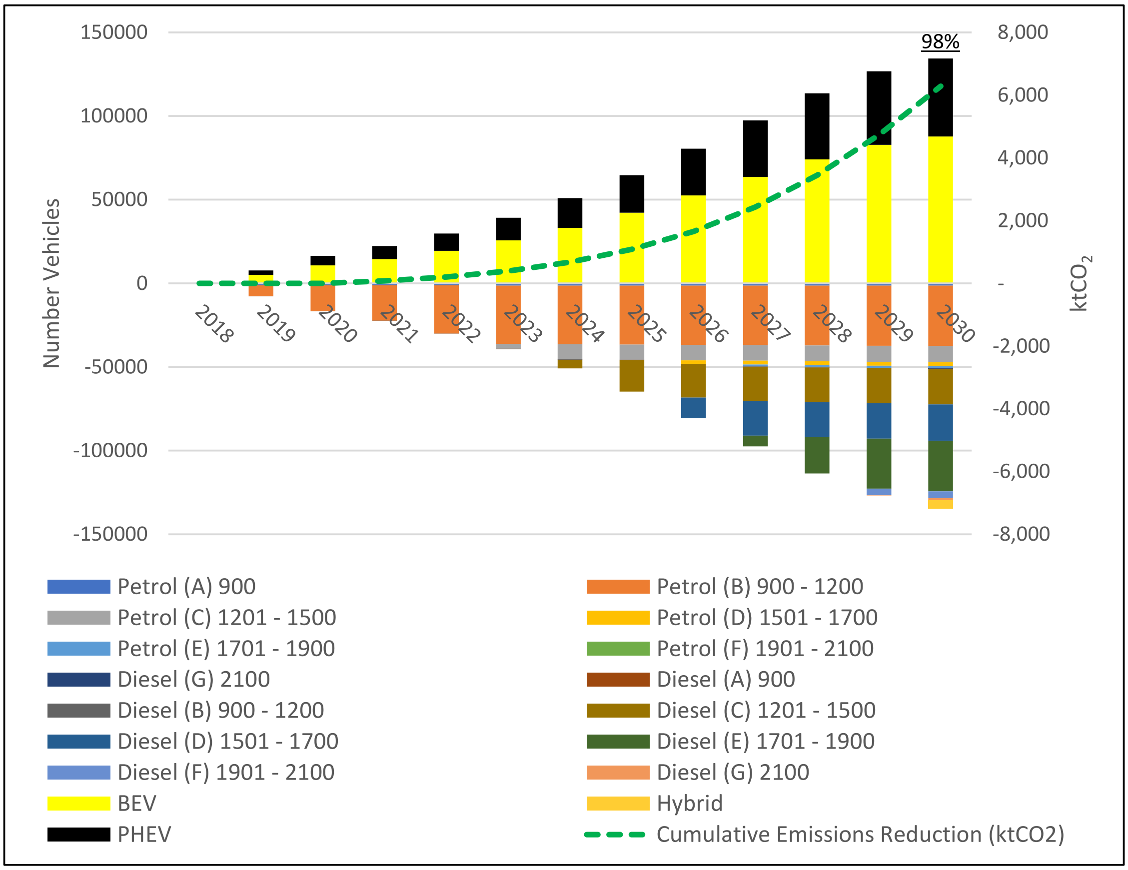

Fig. 5. CAP EV compliant scenario, vehicle sales and cumulative emissions reduction (ktCO2).

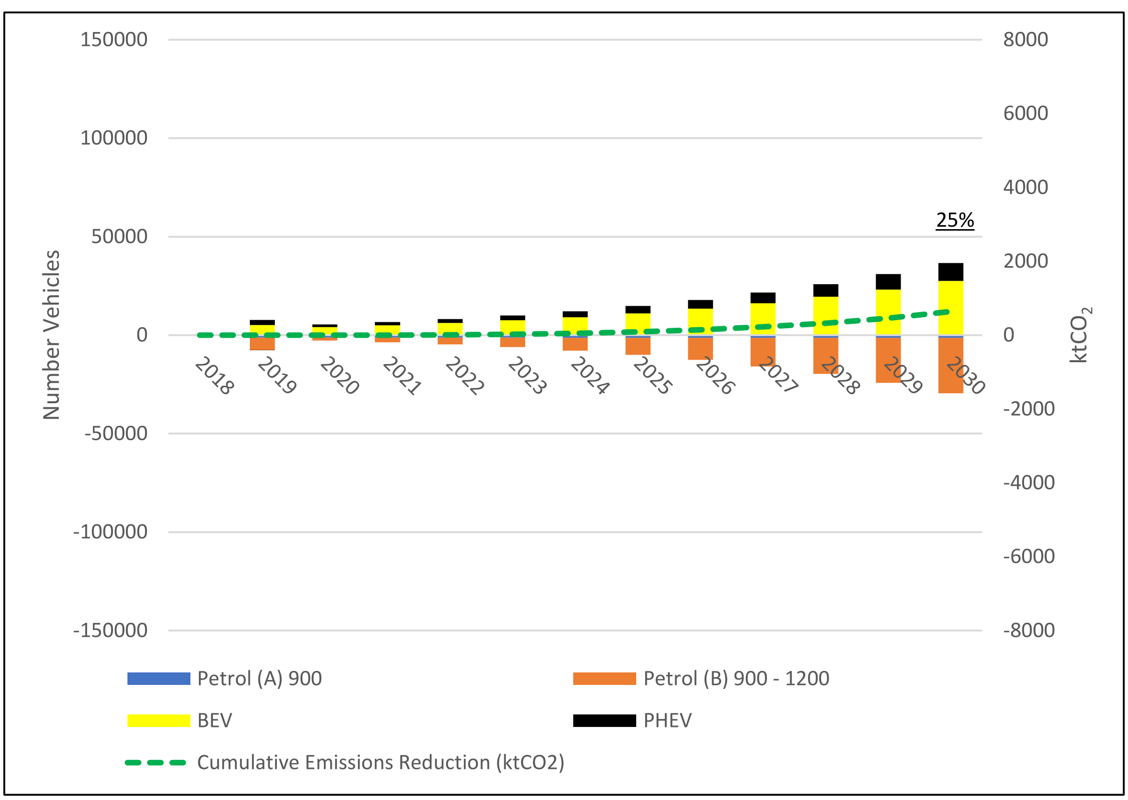

Fig. 6. EV Norway scenario, vehicle sales and cumulative emissions reduction (ktCO2).

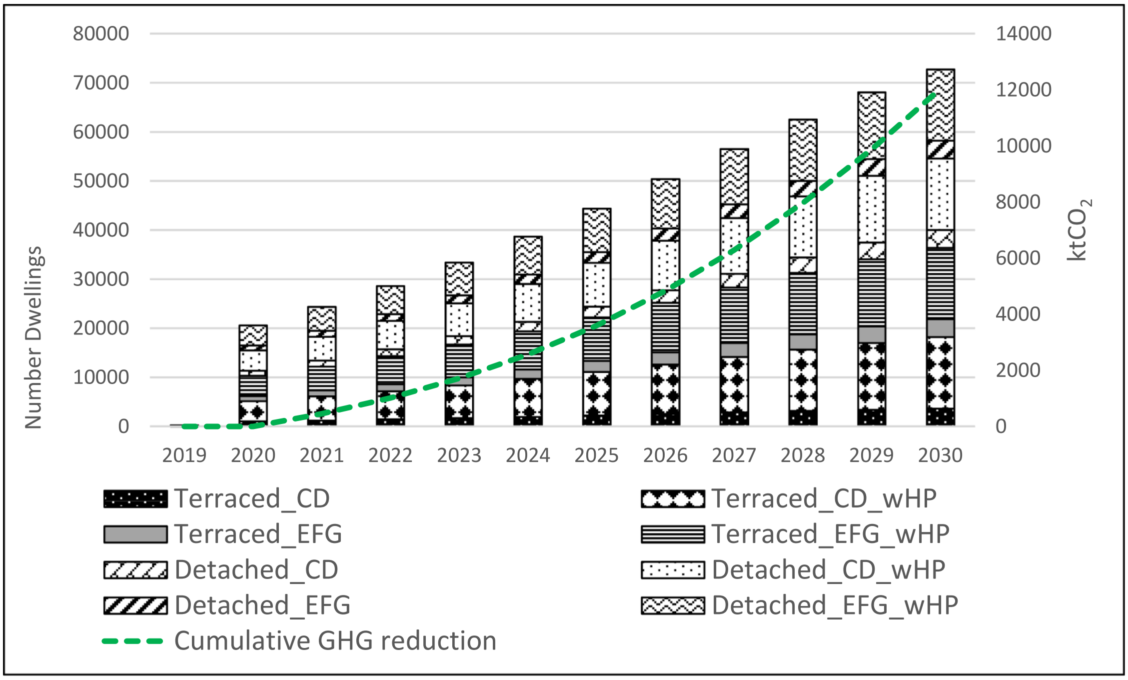

Fig. 7. CAP retrofit compliant scenario, dwelling archetype retrofits and cumulative emissions reduction (ktCO2).

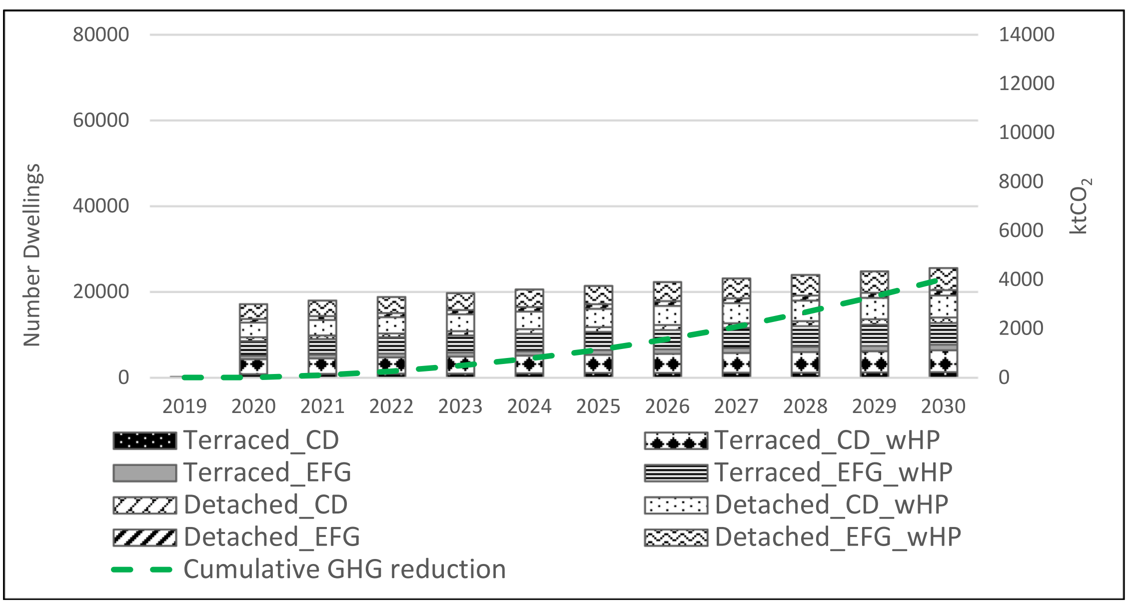

Fig. 8. AdInS scenario, dwelling archetype retrofits and cumulative emissions reduction (ktCO2).

delivers 235,000 deep retrofits (47% of CAP target) is at a scale that is substantially higher than anything which has been achieved to date. This emphasises the significant emissions savings gap which exists between aspirational policy targets and what is feasible. Delivery of both precedent scenarios achieves 4.6 MtCO2eq, representing approximately 25% of the potential reduction associated with the existing policy compliant targets.

Fourth, the introduction of diffusion rates and adopter categories provides a mechanism to tailor policy formation to the specific characteristics of early and mainstream market actors. It is logical to assume that there is a relationship between the coefficient of innovation (p) and imitation (q) and policy interventions. It is important to note that a future target does not necessarily equate to a current policy, or group of policies. An equivalent increase in the coefficient of innovation associated with policies that support early adoption e.g., EV subsidies. However, the direct policy implications and links which are presented in this study relate more to the adoption phase (early/ mainstream market actors) and less to the specific policy.

For EVs, there are multiple policy implications as we seek to normalise the widespread adoption of EVs and gain access to mainstream market actors, who are typically more influenced by financial incentives, including purchasing incentives, free charging, free parking, toll free motorway access, and tax reliefs etc. This type of financial incentive has been present in Norway for over twenty years, examples include registration tax exemption, free toll roads/ ferry's, free parking, lower company car tax, VAT exemption, bus lane access, and a range of charging infrastructure financial supports. 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.

For deep retrofitting, the limited data relating to early adopters presents a policy challenge, as it is likely many free riders exist within the 526 homes which participated in PDRG during the period 2017 – 2020. Additionally, as the average energy efficiency achieved as part of the PDRG is significantly greater ($\leq$ 75 kWh/m^2/year) than that expected within the current CAP target ($\leq$ 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) be sustained or grow in order to achieve higher uptake 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.

This study and associated methodology can support the decision-making process and aid in policy prioritisation and resource allocation. The methodology presented here could be used to recommend future policy targets based on its strong theoretical/ empirical foundation, providing a robust ex-ante evaluation of realistic future policy targets in place of ex-post feasibility checking of existing ones. While the authors acknowledge that the key assumptions and some of the diffusion rates are exploratory, the analysis provides a pragmatic perspective on the implicit diffusion rates associated with existing end year targets. Current end year targets are effectively technology dissemination targets which are not necessarily founded in realistic or comparable technology diffusion rates. The p and q values associated with the EV Norway and AdInS scenarios provide this comparison and serve to highlight the unprecedented nature of the require p, q values needed to deliver Ireland's ambitious climate policy targets. A further application of this method could be the use of the implicit diffusion rates presented here to set technology diffusion targets.

Declaration of Competing Interest

None

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