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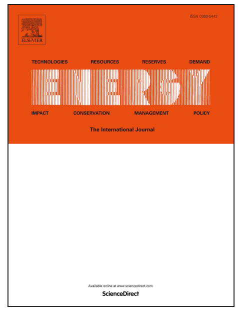

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From Technology Pathways to Policy Roadmaps to Enabling Measures – A multi-model approach

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Abstract

Integrating a range of complementary energy models is becoming an increasingly common method for informing low carbon energy pathways at both national and global levels. Multi-modelling approaches facilitate improved understanding of the detailed *technology pathways* required to meet decarbonisation targets; however, to-date there has been limited attention on the *policy roadmaps* and *enabling measures* that might achieve these decarbonisation targets. This paper addresses this gap by developing a multi-model approach using an energy systems *optimisation* model, a sectoral *simulation* model together with scrutiny of individual policy *measures* to explore decarbonisation of the private car sector in the Irish transport system commensurate with an 80% reduction in national carbon emissions by 2050. The results comprise a cost optimal technology pathway for private cars in a future energy system constrained by a maximum level of carbon emissions, a policy roadmap identifying annual changes in energy efficiency, renewable energy and electrification, and a suite of enabling measures including changes to vehicle registration tax, a biofuel obligation on suppliers and a suite of measure to increase the share of electric vehicles in the fleet. The level of confidence in the different enabling measures to achieve the policy goals is compared and discussed.

1. Introduction

The recent focus on long-term global greenhouse gas emission (GHG) mitigation has led to the production of a wide array of energy and emission specific models with varying levels of sectoral and geographic focus. On the one hand, optimisation models are beneficial in determining a *technology pathway*, adept at depicting what technological changes are needed in an energy system subject to a constraint, usually GHG emissions, although with little or no indication of the required policy measures, e.g., the European Commission's 'Energy Roadmap to 2050' [1] and the International Energy Agency's (IEA) 'Energy Technology Perspectives' (ETP) [2]. On the other hand, simulation models can effectively determine a *policy roadmap* which describe the policy steps and interim targets for emissions mitigation, although not necessarily with a focus on optimising around a certain scenario, e.g., the IEA's World Energy Outlook (WEO) [3] and the Irish 'National Renewable Energy Action Plan' (NREAP) [4]. Finally, analysis of these policy roadmaps can subsequently identify how *enabling measures* can achieve particular emission mitigation targets at a national or sectoral level through ex-ante and ex-post analysis of policies, e.g., regulations placed on car manufacturers, eco-labelling of appliances, etc. [5]. This paper brings together these three aspects in a coherent consistent iterative framework and explores the interactions, the development from one to another and highlights the need for more analysis on the effectiveness, certainty, and timing of specific measures.

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The European Union (EU) face challenges in meeting emissions reduction targets in the short term (to 2020) and establishing realistic targets in the longer term (from 2030 to 2050). The European Commission's report on moving to a competitive low carbon economy in 2050 predicts that transport will be the most difficult carbon dioxide (CO_2) emitting sector to decarbonise in the long-term, and is the only sector foreseen to have an increase in emissions in the medium-term [6]. Efficiency measures and biofuel blending are seen as means of meeting short-term targets (although the latter is limited by blend walls in internal combustion engines (ICE)); however, the primary challenge of decarbonising transport lies in shifting away from petroleum based liquid fuels. There is a clear and urgent need for useful methods to effectively plan and inform the implementation of policy measures to go beyond European short term targets and address this challenging long-term decarbonisation of the transport sector.

It has become common practice to address this need for planning through the integration of energy models. This integration provides results of greater value by combatting the weaknesses in one model with the strengths of another. This multi-model approach has been adopted and applied to a number of model types using varying degrees of integration. In its lightest form, two models are run independent of each other with the results of each compared until a convergence is reached giving way to a stronger result set through a low level of model structuring and a more versatile procedure than a fully integrated model, yet is more susceptible to errors arising due to potential inconsistencies between both model types. In the heaviest form, a complete integration of two or more models is carried out, requiring both models to be built within the same mathematical format, combatting the inconsistencies between modelling techniques, yet increasing complexity and processing power. An intermediate form creates a scaled-down representation of the structure of one model in another through integrating a reduced level of detail between model types.

A very common method of this intermediate model integration has been between computable general equilibrium (CGE) models and energy supply models, e.g., the macroeconomic model (MACRO) with a detailed energy supply model (MESSAGE) [7], and a CGE model (GEM-E3) with an energy optimisation model (TIMES) [8]. Integration of sectoral specific models have also been evident, e.g., a power systems model (PLEXOS) linked with an energy systems model (TIMES) [9], and a three-way integration of MESSAGE, TIMES, and a unit commitment optimisation tool (REMix-CEM-B) to analyse the potential of concentrated solar power in Brazil [10]. A broader, long-term analysis of the EU2030 goals was carried out with a similar analysis for Serbia combining the generic optimisation program (GenOpt) and the simulation model (EnergyPLAN) [11].

There have been very few studies dealing with the integration of transport focused models and broader energy systems models while within the few reviewed, the authors' found no representation of the individual policies necessary to achieve the policy roadmaps identified. For example, a MARKAL model of household and industry transport activities was integrated with a CGE model and outlined the potential carbon mitigation under a Kyoto target, yet gave no indication of the specific measures required [12]. A South Africa based study soft-linked five models to create long-term projections of the transport sector which consisted of developing and linking a CGE model, a vehicle parc model, a time-budget model, a freight demand model, and a fuel demand model. While this study considers the CO_2 mitigation from policy roadmaps (such as shifting from private to public transport), it fails to consider the individual policies measures which may enable this shift [13].

The method of model integration presents a concise improvement from individual modelling detail and results, yet there is still a disconnect between modelling and policy analysis as described in this literature review above, especially in the area of transport, which is remarkable given the sizeable task of decarbonising transport necessary to adhere to a low carbon future. This paper aims to bridge this gap in energy modelling through (i) employing a soft-linking methodology between a least-cost optimisation model of the Irish energy system (Irish TIMES (The Irish Integrated MARKAL-EFOM System) [14]) and a sectoral simulation model of the private transport sector in Ireland (the CarSTOCK model [15]) and (ii) through using ex-post and ex-ante analysis to determine the specific enabling policy measures. Optimisation models are capable of exploring the implications of different levels of emissions reduction ambition for energy system evolution and can outline potential technology pathways; simulation models can show how particular policies and interim targets can deliver a particular energy system and hence point to policy roadmaps; finally, ex-post and ex-ante analysis facilitate analysis of enabling policy measures. The integration of these modelling and analytical approaches allows for a comprehensive description of how to decarbonise a particular sector, in this case the private car sector in the Irish energy system. The reason Ireland is chosen as a case study is twofold: first, it has the 4th highest transport emissions per capita of all EU member states (in 2014 Ireland was 2.43 tCO_2/capita whereas EU average was 1.62 tCO_2/capita) highlighting the onerous task of decarbonisation [16]; second, it has been a case-study for multi-modelling approach in the past, integrating Irish TIMES with the power sector [9] and the transportation sector [17].

This paper explores an ambitious long term scenario based on the European Commission's recommended CO_2 greenhouse gas emissions reduction by 2050 of 80% - 95% relative to 1990 [18]. This is in keeping with the Irish national policy position on climate change which declares a long-term vision guided by *"an aggregate reduction in carbon dioxide ($C0_2$) of at least 80% (compared to 1990 levels) by 2050 across the electricity generation, built environment and transport sectors…"* [19]. A constraint of 80% CO_2 emissions reduction by 2050 relative to 1990 is entered into Irish TIMES, which determines the least-cost solution in all sectors of the economy (agriculture, residential, commercial, industry and transport). This analysis forms the basis for scenario and policy development in the CarSTOCK model, which in turn is used to analyse the type and timing of specific policy measures that can help achieve long-term decarbonisation. The efficacy of enabling policy measures requires individual scrutiny that depends on a multitude of factors which are discussed in this study – who is targeted by the measures, what type of instrument is employed, what is the timeline of these measures, and what level of change will be required. The paper is organised as follows, section 2 describes the modelling and analytical methodology, section 3 presents the results, and section 4 concludes.

2. Methods

This section first describes and defines technology pathways, policy roadmaps and enabling measures; it then describes the three technical tools employed, namely the Irish TIMES energy systems optimisation model, the CarSTOCK simulation model and ex-post analysis of policy measures; lastly, it describes the multi-model approach that integrates these three tools together.

2.1. From Technology Pathways to Policy Roadmaps to Enabling Measures – A Multi-Model Approach

Technology pathways can be broadly defined as the timing, quantity and combination of technologies required to achieve a certain policy target (e.g. an 80% reduction in energy system emissions) by a given end-point (e.g. 2050), e.g., the European Commission's Energy Roadmap to 2030 [1], and the IEA's ETP [2]. They are typically expressed in terms of energy, emissions, and rates of technology diffusion over time (e.g. Megawatt hours, tons of CO_2, % share technologies). Technology pathways are frequently generated in optimisation models that select technologies such that the overall system cost is minimized. In this way, individual sectors (e.g. transport, residential, industry) are optimised according to overall system needs, e.g. what is cost-optimal for the transport sector by itself might be different for what is cost optimal for the transport sector as considered within the entire energy system. Model generated technology pathways will normally need refinement by modellers in order to ensure realism for sectoral results.

Least cost technology pathways purport to model the market dynamics whereby new technologies with the greatest cost advantage are optimally diffused over time. However, in reality, many factors associated with technology diffusion (e.g. information costs, decision-making inertia, inconvenience costs) are not adequately included in the price of the technology. Therefore policy intervention (e.g. favourable tax incentives) can be required to align the characteristics of low carbon technologies with market signals such that they diffuse at the necessary rate to achieve the policy target. While models that generate technology pathways can be refined to more accurately model technology diffusion (e.g. through a market share algorithm), models that generate technology pathways are usually not designed or equipped to model direct policy intervention.

Policy roadmaps can be broadly defined as a combination of policy goals, such as interim and final % penetration targets, and the strategies for achieving these goals, such as increased energy efficiency, increased renewable energy, fuel switching, etc e.g., the IEA's WEO [3], and Ireland's NREAP [4]. Within a multi-model approach, simulation models with their greater temporal and technical resolution can i) test the feasibility of technology pathways generated in optimization models, and ii) simulate the policy roadmaps that align with these technology pathways. To prepare a policy roadmap based on a technology pathway, each newly diffused technology from the technology pathway must be examined and considered in light of what policy will be expected to facilitate or accelerate its diffusion. In a simulation model a single scenario can be designed to simulate the progressive penetration of a particular technology. The resulting policy roadmap could therefore outline a feasible combination of energy efficiency, renewable energy, and fuel switching - expressed in terms of interim targets at key intervals - that achieve a final overall target.

For certain technologies, an associated policy roadmap will be an almost one to one matching of policy for technology; however, some technologies cannot easily be diffused by one or two policies and for such technologies, a suite of policy measures will be required - policy mixes, especially of different policy types, are usually more successful than single policies [20]. For technology diffusion, there is evidence that the formative phase for new technologies which are more similar to existing technologies (i.e. more substitutable) and which result in an almost identical energy service are shorter; by contrast, the formative phase for new technologies that are less directly equivalent to existing technologies (i.e. less substitutable) are longer [21]. Based on these previous findings, it can predicted that of the range of new technologies in the technology pathways and policy roadmaps analysis, the technologies with less equivalence to incumbent technologies will require larger and more diverse policy mixes and the technologies with greater equivalence to incumbents will require fewer and less diverse policies mixes.

To determine what *enabling measures* might help diffuse the array of technologies outlined in the technology pathways and policy roadmaps, ex-post and ex-ante analysis of policy measures is used. Ex-post analysis of previous and similar measures can provide important insights from the success rate of previous policies. Energy policies rarely achieve their expected targets – whether overachieving or underachieving. This can be for many reasons, including insufficient incentive. Ex-ante analysis of the policies or combinations of policies likely to succeed are crucial for decarbonisation strategies to be successful. The iterative process used which flows from technology pathways, to policy roadmaps, to enabling measures is shown in Figure 1. Technology Pathways - Irish TIMES Optimisation Model

Technology Pathways have been established in the past using the Irish TIMES energy systems model [14]. The Irish TIMES model is a partial equilibrium optimisation model of the Irish energy sector, initially developed to build a range of medium and long term scenarios that provide insights to the technology requirements for energy system decarbonisation. The model was built under a TIMES framework, a technical economic model generator for local, national and multi-regional energy systems which operates with the objective function to maximise the total surplus and provide a technology-rich least-cost linear optimisation basis for the estimation of energy dynamics over a long-term, multi-period time horizon [22]. The model simultaneously solves for the least cost solution subject to emission constraints, resource potentials, technology costs, technology activity and capability to meet individual energy service demands across all sectors (see Equation 1). The model minimises the net present value (NPV) through the selection of technologies with resulting energy consumption and CO_2 emissions output.

$$NPV = \sum_{t=1}^{NbPer} \left[(1+\delta)^{1-t} * Annual\ Cost(r,t) * \sum_{a=1}^{NbYrsPerPer} (1+\delta)^{1-a} \right] \quad (1)$$

Where:
δ – Discount Rate
NbPer – Number of periods over the horizon
NbYrsPerPer – Number of years per period
Annual Cost – Sum of all costs
r – Set of regions in the area of study
t – Time period

The Irish TIMES model was built by applying localised data and assumptions to the Pan European TIMES (PET) model, a model of 36 regions of Europe (EU27, Iceland, Norway, Switzerland, and six Balkan countries) [23]. The model represents the potential long-term evolution of the Irish energy system through a network of processes which transform, transport, distribute and convert energy from its supply sector to its power generation and demand sectors. Energy demands are driven by a macroeconomic scenario covering the period to 2050, which is based on the Economic and Social Research Institute (ESRI) Harmonised Econometric Research for Modelling Economic Systems model (HERMES) of the economy which is used for medium-term forecasting and scenario analysis of the Irish economy underpinning the 2013 edition of the ESRI's Medium-Term Review [24].

The private transport sector in Irish TIMES is driven by exogenous projections of passenger kilometres based on gross national product (GNP) per capita and the number of cars per household coupled with income elasticities of demand determined by the HERMES model. The model chooses from a set of technology and economic attributes that vary over time within the model to meet this demand at least cost while constrained by an overarching long-term reduction in CO_2. Market share of new vehicles is exogenously calculated using a discrete choice model which accounts for tangible costs of vehicles in competition with each other, such as capital costs, fuel cost, and operation and maintenance costs, as well as intangible costs, such as range anxiety, and model availability (see Table 1). Further description of the underlying assumptions, corresponding data, and sources of TIMES and of the discrete choice model may be found in the 'Data in Brief' supplement to this paper.

2.1.1. Policy Roadmaps - CarSTOCK Simulation Model

Irish based policy roadmaps have been established in the past by the CarSTOCK model [25]. The CarSTOCK model is a sectoral simulation model of the private transport fleet in Ireland that projects the evolution of the private car stock, energy use and related CO_2 emissions from 2013 to 2050 based off the ASIF methodology developed in [26] which can be summarised by Equation 2. In brief, total private transport related CO_2 is calculated as a sum of the product of vehicle activity (A), private car stock (S), energy intensity (I), and emission factors (F) for fuel type (f) and vintage (v).

$$Transport\ Related\ CO_2 = \sum_{f,v,m} A_{f,v,m} * S_{f,v,m} * I_{f,v,m} * F_f \tag{2}$$

A stock profile is built based off a database acquired from the vehicle registration unit in Ireland detailing the evolution of the car fleet between 2000 and 2013 disaggregated by fuel type and vintage of the vehicles. This database was used to create a survival profile for each private car fuel type of varying engine sizes (ES) using Equation 3.

$$Survival\ Rate_v^{ES} = Average\left(\frac{(Stock_v^{ES} - Stock_{v-1}^{ES})}{Stock_v^{ES}}\right) * (1 + Survival\ Rate_{v-1}^{ES}) \tag{3}$$

Mileage and specific energy consumption of the historic fleet, also disaggregated by engine band, were obtained from the Irish national car test results, a compulsory vehicle inspection in Ireland which records data relating to the road worthiness of all private cars on a bi-annual basis for cars under ten years old, and annually beyond this.

The model uses a combination of income and fuel elasticities of demand based off [27] to calculate the total level of sales, stock and vehicle kilometres in the country per annum. Projections of these variables are calculated using exogenous inputs of income from the computer general equilibrium (CGE) model HERMES, as before with TIMES.

The CarSTOCK model allows for a more detailed evolution of the private car fleet relative to the results from the Irish TIMES model. This proves more effective at presenting an insight to the policies and individual measures which allow for the reduction of CO_2 emissions amongst private cars and subsequently assesses the feasibility of the results from Irish TIMES. For example, Irish TIMES only considers one technology per fuel type, e.g., petrol vehicle or diesel vehicle, while CarSTOCK has the functionality to disaggregate by vehicle type, i.e., small (engine size less than 1300cc), medium (between 1301cc and 1900cc) and large (greater than 1900cc). The purpose of this split is to improve heterogeneity through disseminating driving patterns more accurately as owners of small vehicles have been known to drive less per year than those owning larger vehicles [28]. Heterogeneity is accounted for using a market share algorithm, in the same way as described in the Irish TIMES model. A more detailed analysis of this, along with additional details of the structure and operability of this model can be found in the 'Data in Brief' supplement.

2.1.2. Enabling Measures - Ex-post and Ex-ante analysis of Policy Measures

Policy measures, with a specific focus on energy efficiency improvement and fuel switching for private cars, were used for scenario development within the CarSTOCK model. These measures were chosen to simulate a corresponding level of decarbonisation against a baseline, which assumes no policy incentive to switch to alternative fuelled vehicles from the base year onwards, against the low carbon results from the Irish TIMES model. Three measures in particular were focused upon in aiming to achieve the low carbon results as laid out by TIMES; efficiency improvements of ICEs, increased biofuel blending, and measures to promote the penetration of alternative fuel vehicles.

The former two of these policy measures have proved successful in both Ireland and across Europe in the past decade as the target of the measures has been toward suppliers rather than the consumers – toward manufactures for regulations relating to efficiency improvements, and toward fuel suppliers for regulations relating to biofuel blending - allowing for a somewhat easier implementation. However, the potential of these measures has been identified to be considerably more limited than that of alternative fuel vehicle penetration, yet the impact of measures encouraging the sale of these vehicles is subject to a much larger degree of uncertainty. Ex-post and ex-ante analysis of these policy measures is used to develop scenarios capable of achieving the policy roadmap laid out by the CarSTOCK model, which assesses the feasibility of achieving a low carbon transport technology pathway as identified by Irish TIMES.

2.1.3. Multi-Model Approach

The soft-linking methodology employed in this study can be described as a light form of integration through model coherence, which is graphically represented in Figure 1 above and complemented by Table 2 below. A long-term CO_2 emission reduction is first entered as a user constraint in the Irish TIMES optimisation model which in turn generates a technology pathway for each sector of the Irish energy system. The technology pathway from the private car sector is extracted, in particular the effects of energy efficiency improvements in the private car fleet combined with fuel switching, which are used in generating policy roadmaps in the CarSTOCK simulation model with the aim of informing the specific policy measures necessary to meet the technology requirements laid out by Irish TIMES. An ex-ante and ex-post approach, described in section 2.4, is employed to determine the individual policy measures necessary to contribute towards a long-term low carbon scenario.

2.2. Scenario Development

The scenario development of this paper is initially driven by a low carbon scenario generated by Irish TIMES, providing a cost optimal technology pathway for the transport sector in contributing toward a low carbon future (Section 2.6.1). Scenarios are subsequently generated within the CarSTOCK model, identifying the policy roadmaps required to achieve the technology pathway laid out by TIMES, and finally ex-post and ex-ante analysis of measures is carried out to show how to enable measures to achieve this policy roadmap (section 2.6.2 – 2.6.4)

2.2.1. Low Carbon Scenario

An assessment report released from the Inter-Governmental Panel on Climate Change (IPCC) defined CO_2 as “the most important anthropogenic greenhouse gas” with the atmospheric concentration of CO_2 in 2005 significantly exceeding the natural levels ranging over the last 650,000 years [29]. Concerns about GHG emissions interfering with the international climate has resulted in the Copenhagen Accord which established a political consensus on limiting mean global temperature increase to 2°C which must be met through a substantial reduction in GHG emissions. The IPCC Assessment Report shows that to meet this target it is required for global GHG emissions to be reduced by at least 50% by 2050 relative to 1990 levels [30]. The EU has determined that in meeting this target, industrialised countries should contribute more than the average international requirement and have advised between an 80% to 95% reduction by 2050 relative to 1990. This paper focuses on policy evaluation of the private transport sector using a scenario dealing with a reduction in CO_2 emissions of 80% by 2050 relative to 1990.

2.2.2. Improved Efficiency

The most noteworthy policy attempt to steer consumer choice of private cars towards more efficient vehicles was from a change in the basis of taxation on motor vehicles in 2008, which was previously based off the size of a vehicle’s engine and has been changed to correspond to level of emissions from a vehicle (in gCO_2/km) which resulted in a significant migration in the private car fleet to more efficient vehicles [5]. This policy measure acted as a supplement to the formal adoption of CO_2 performance standard regulations as decreed by regulation EC 443/2009 of the European parliament which sets a target for specific emissions of $95gCO_2/km$ to be in effect by 2021 [31]. A significant reduction in new car test emissions was experienced across the 28 EU member states in the years following the adoption of these targets (see Figure 2) [32].

Energy efficiency improvement policy measures are implemented in CarSTOCK through national targets of new car emissions, with the magnitude of these targets based off the Irish TIMES model. An upper bound is placed on this energy efficiency improvement based off a combination of results from a review of potential vehicle improvements [33] and an International Energy Agency study which analyses the max potential improvement in fuel economy in private cars [34]. The maximum efficiency improvements of petrol, diesel, and hybrid vehicles by 2050 relative to 2008 was subsequently chosen to be 45%, 47%, and 52% respectively.

2.2.3. Biofuel Blending

There has been an increase in the level of bio-ethanol and bio-diesel blending with petrol and diesel in Ireland respectively since the introduction of the Biofuel Obligation Scheme (BOS), which obliges suppliers to derive at least 8.695% of motor fuels placed on the market from a renewable source as of the 1st of January 2017 [35]. This statutory instrument serves as a response to the binding 10% renewable energy in transport (RES-T) target introduced by the Renewable Energy Directive (RED) in 2009, and to date has proved effective at increasing the level of blending in transport in recent years [36].

Biofuels are effective at contributing towards short term targets, although the relatively lower energy density of bio-ethanol and bio-diesel with respect to their petroleum based counterparts renders achieving the RES-T target solely through the use of biofuel blending to be very difficult[2]. The yellow band in Figure 3 represents the range of possibilities of the RES-T target if it was to be met solely through biofuel blending, the lower limit representing a case whereby the target was to be met through bio-diesel alone (which has a calorific value of 33 Megajoules per litre (MJ/ltr) compared to 36 MJ/ltr for diesel), the upper limit through bio-ethanol alone (which has a calorific value of 21 MJ/ltr compared to 32 MJ/ltr for gasoline), and the centre through a combination [37].

The level of blending of biofuel with petrol and diesel is limited for conventional ICEs to 5% and 7% according to European fuel standards EN 228:2004 and EN 590:2009 respectively, although allowances have been made for both to reach a figure as high as 10% at both a national and regional level, in accordance with the Fuel Quality Directive, for use in conventional ICEs, provided sufficient information is made available to the consumer regarding the fuel blend [38]. This study uses a linear extrapolation of historic bio-ethanol and bio-diesel blending with growth capped at the limits imposed by these European fuel standards in the primary scenario, and a limit placed on the use of bio-fuels of 10% in the secondary scenario, with the green and blue bands in Figure 3 representing the potential of blending using bio-diesel and bio-ethanol respectively.

The use of Hydrotreated Vegetable Oil (HVO) (also referred to as 'Renewable Diesel') has the potential of overcoming the limitations imposed by the European fuel standards outlined above. HVO is a diesel based fuel traditionally produced from vegetable oils, but recently derived more commonly from waste and residue fat fractions coming from food, fish and slaughterhouse industries, which are hydrogenated and used in an isomerization process to produce a fuel which can entirely substitute diesel [39]. The requirement of hydrogen in the hydrogenation process limits the economics of HVO production, therefore this study follows a scenario development based on a range of HVO blending rates to determine its potential long-term decarbonisation effect.

2.2.4. Alternative Vehicle Penetration

The effect of incentivising battery electric vehicles (BEV) and plug in hybrid electric vehicles (PHEV) purchasing through policy measures are considerable more cumbersome to enable when compared against the effects from bio-fuel blending and efficiency improvement mandates, as the latter two can be enforced on the supply side of the chain while the former relies solely on consumer behaviour. Despite this, a multitude of countries have invested in a myriad of incentivising schemes with the hope of shifting consumer transport preference towards electrification. Norway currently benefits from the highest electric vehicle market share in the world (23% in 2015) [40]. There are a range of contributing factors to this market share – Norway's high GDP per capita, membership on the Electric Vehicles Initiative board, and strong incentives in the form of registration tax reduction, e.g., Value Added Tax (VAT) exemption, waivers on road tolls and ferries, and access to bus lanes [40]. It is onerous to deduce the exact contribution any one incentive has on shifting consumer preference towards BEVs, and so this paper only considers the cumulative effect.

Figure 4 summarises the historic policy measures which have been introduced to encourage BEV purchasing in Ireland. The county of Cork took additional measures to promote BEV purchasing beyond those already offered at a national level which saw a relative increase in sales compared against all other county performance. Despite the cumulative incentives on offer, Ireland is still not on track to meet its current 2020 target of 50,000 BEVs (see Figure 4). This study uses the market share profiles described in the supplementary material based on a range of policy roadmaps and later identifies potential contributing policy measures.

3. Results

The results of the approach outlined above is presented in three distinct sections; *Technology Pathways* – the initial results from the TIMES optimisation model, detailing the optimal technology mix within the transport sector in contributing toward a 80% reduction in CO_2 emissions by 2050 relative to 1990, *Policy Roadmaps* – the results from the CarSTOCK model, detailing the specific policy packages necessary to contribute toward

[2] The RES-T target is an energy based target, meaning a 10% blend of bio-fuels with fossil fuels will not be enough to achieve 10% RES-T due to the lower calorific value of biofuels relative to petrol and diesel.

achieving the technology mix outlined by the TIMES model, and finally *Enabling Measures* – detailing the individual measures capable of contributing toward the policy packages outlined by the CarSTOCK model.

3.1. Technology Pathways

In the business as usual scenario, the transport sector sees a 'dieselisation' of the private car fleet, which follows the trend experienced in recent years due to the lower level of cost of taxation associated with the relatively lower emissions when compared against petrol [5]. A low level of liquid petroleum gas fuelled vehicles are employed to meet the marginal passenger kilometres demand remaining generated by the model which are not already met by conventional ICE technologies.

With the 80% CO_2 emissions reduction imposed on the energy system, the private transport sector is determined as a relatively cheap means of decarbonising the energy system, as the TIMES model calculates a substantial 97% reduction of CO_2 emissions in contributing towards the full energy system decarbonisation. The technology pathway created by TIMES under this scenario constraint is calculated in two forms; energy efficiency improvement and penetration of alternative fuelled vehicles. The fuel economy of petrol and diesel cars in 2040 is reduced to 16% and 18% of their 2015 values respectively. Regarding fuel switching, the private transport sector is initially fossil fuel dominated, with plug in hybrids becoming cost competitive from 2020 onwards, achieving a near-full market penetration by 2045, at which point BEVs begin to emerge in the market. The combined effort of these two effects reduce private car related CO_2 emission from 5,940 ktCO_2 in 2015 to 170 ktCO_2 in 2050 (see Figure 5).

3.2. Policy Roadmaps

The technology pathways developed in the Irish TIMES model are used to generate a range of policy roadmaps in the CarSTOCK model, capable of satisfying the same level of decarbonisation according to the technology investments laid out by the TIMES CO_2-80 scenario.

The efficiency standards described by the technology pathway above are aimed to be met through a combination of technology efficiency improvements in conventional ICEs (energy efficiency) and an increase in the bio-fuel blending (carbon efficiency). The former is introduced in the model via a year-on-year fuel economy improvement in keeping with the resultant technology efficiency in TIMES. The latter is represented by altering the fuel composition time series input to signify an increase in bio-diesel and bio-ethanol, described by Figure 3. The combined effect of the efficiency improvements contribute towards a decarbonisation reduction level of 4.5% by 2050 relative to 2015 – the improvement in efficiency is roughly offset by the long-term expected growth in vehicle demand. The 2020 RES-T target proves incredibly onerous to be met through bio-fuel blending alone from the varying energy density of fuel types. In 2015, the gasoline to diesel ratio stood at 1:2.2, yet the relatively lower energy density of bio-ethanol relative to bio-diesel suggests that the rate of bio-fuel blending will need to increase at a much faster rate in the short term to represent 10% of transport energy by 2020. Based off the current trajectory, Ireland will not meet its RES-T target.

The vehicle stock rates for each technology are roughly replicated through altering preference rates in the market share algorithm, presenting four unique policy roadmaps. Capital costs, operation and maintenance costs, and fuel costs are held constant for all vehicle types, while the intangible costs are varied for alternative fuelled vehicles presenting 4 unique scenarios for the purpose of this study: (i) 'No Preference Change' where the intangible costs are held constant for all technologies, (ii) 'Gradual Preference Change' where intangible costs for BEVs and PHEVs decrease at a rate of 1% per annum, (iii) 'Rapid Preference Change' where this rate increases to 2%, and (iv) 'Aggressive Preference Change' where this rate increases to 3%. The resulting stock penetration is presented in Figure 6 below.

Both the 'No Preference Change' and 'Gradual Preference Change' scenarios fail to present a significant penetration of PHEVs or BEVs, although preference has a natural shift towards diesel based vehicle technologies over petrol based forms allowing for a second option of decarbonisataion to be analysed in the form of increased HVO blending with diesel fuel. A blend of 20% HVO in 2050 has little effect (16.6% reduction, due to the blending limits of bio-fuel being reached prior to this). A more extreme 100% HVO blend by 2050 has a resultant 92% reduction, achievable due to the aforementioned diesel preference shift. Increased PHEV and BEV penetration contribute towards 17%, 58% and 90% CO_2 reduction in in the Gradual, Rapid, and Aggressive Preference Change scenarios respectively (see Figure 7). BEVs become notably cost competitive in the latter two scenarios which proves essential in contributing towards a low-carbon policy roadmap[3]. Combining the 'Aggressive Preference Change' scenario with a 100% blend of HVO provides a total maximum decarbonisation of 95% by 2050.

3.3. Enabling Measures

Individual policy measures can be described as both 'invisible' measures, requiring an energy transition on the supply side where little or no societal change is required as consumers see no difference – as is the case with mandates on vehicle manufactures and fuel suppliers - and 'visible' measures requiring a large societal change to prove effective – such as incentivising electric vehicle purchasing.

Efficiency standards (invisible measures) can be met through an international assignment of CO_2 specific standards, as with the 95 gCO_2/km mandate, of 80gCO_2/km in 2040 and 75gCO_2/km in 2050. Ireland does not manufacture any cars and is entirely dependent on imports, therefore effective implementation of any efficiency improvements vis-à-vis technology alterations is necessary to be mandated at a European level, although a change in the annual motor taxation reflecting these international targets may contribute on a national level.

Domestic policies can be effectively implemented, as they have in the past, in the form of biofuel blending targets (invisible measures). The BoS can be increased further to 10.13% (currently 8.695%) while staying in accordance with the European fuel standards, assuming the same ratio between gasoline and diesel as of 2015. The blending of HVO with diesel is not constrained by any technical limitations and can be increased indefinitely, but is subject to the economics of production providing a suitable policy measure to aid decarbonisation efforts if the preference shift towards PHEVs or BEVs is insufficient.

Policy measures can be introduced to incentivise the sale of PHEVs and BEVs, although the effect is not as direct or certain as that of technical efficiency improvements or blending obligations (visible measures). These measures include, but are not limited to: (i) a reduction or derogation of vehicle registration tax and value added tax, (ii) a reduction of annual parking costs, (iii) improved charging infrastructure, and (iv) further reduction of capital costs via government grant schemes. Mandating these measures has a much lower level of confidence relative to aforementioned visible measures discussed above, due to the reliance on societal transition rather than energy transition on the supply side.

Policy measures may be targeted to consumers (PHEV and BEV purchasing incentives), the suppliers (such as the BoS), and a mixture of suppliers and consumers (car annual registration tax). The effect on the transportation system of the latter two is much more certain than the former – it is difficult to determine the exact contribution toward consumer preference that these incentives would have.

4. Conclusion

The soft-linking methodology employed in this study goes beyond the traditional multi-model approach by combining the foresight and comprehension of the energy system found in a least-cost optimisation model with the detailed technological representation found in sectoral simulation model with ex-post and ex-ante analysis of individual policy measures to enable long-term low-carbon solutions for the sector in question; in essence, the paper develops and aligns technology pathways to policy roadmaps to enabling policy measures. An optimisation model is capable of determining the least-cost technology pathway to be taken for a given constraint, however it is ill-equipped for informing which policy measures might facilitate this long-term vision, while the technical detail underpinning a simulation model allows for policy roadmap generation. This paper focused on the private car sector and identified a range of policy measures capable of meeting the technology pathway created by the Irish TIMES model with the CarSTOCK simulation model under an 80% reduction of CO_2 imposed on the entire energy system.

Table summarises the list of outputs from each iteration of this method.

[3] For the purpose of this paper, only the emissions related to the transport sector are considered, in accordance with the UNFCCC reporting standards. CO_2 emissions generated due to the additional electricity generation are calculated within the power sector in TIMES, so only tail-pipe emissions are considered, and is taken as 0 gCO_2/km for BEVs.

4.1. Policy Recommendations

In the short-term, and based on the current diesel-gasoline share, mandatory bio-fuel blending obligations imposed on suppliers can be increased to 10.13% (which is keeping in accordance with the current fuel quality standards laid out by the European Commission in the RED) to stabilise national private car emissions out to 2025. This blend would have to be further increased to 13.21% to meet current 10% of renewable energy in transport target for 2020, which exceeds the guidelines for conventional ICE diesel and gasoline blends.

In the medium-term, imposing European-wide technology specific improvement targets on car manufactures trending towards 80gCO_2/km in 2040 and 75gCO_2/km in 2050 stabilises CO_2 emissions in private cars out to 2050, and is sufficient to provide a 4.5% reduction by 2050, relative to 2015, when combined with the aforementioned blending mandates.

In the long-term, an array of incentives can be introduced to promote the use of pure electric vehicles and plug in hybrids, although the effectiveness of these measures are subject to a high degree of uncertainty. In the event of a rapid preference shift towards BEVs and PHEVs (a 2% reduction in intangible costs per annum), there is a consequent 70% penetration of these technologies (split further into 70% PHEV, 30% BEV) by 2050. In an aggressive preference shift (3% reduction in intangible costs per annum), this penetration rate is increased to 95% (21% PHEV, 79% BEV). This level of vehicle electrification satisfies the technology pathways proposed by Irish TIMES, and therefore stands as the cost optimal solution, although due to the level of uncertainty surrounding preference shift, the introduction of HVO blending with diesel fuel is proposed as a secondary long-term solution to decarbonisation. Consumer choice has been switching steadily towards diesel fuelled private cars in recent years [15], and HVO stands as a viable means of producing a carbon-neutral diesel substitute allowing for an effective ‘plan B’ in a low-preference shift towards electrification.

The short-to-medium term targets outlined have a higher degree of certainty regarding effectiveness (as ex-post analysis of similar measures have shown relatively successful deployment to date) relative to the long-term electrification measures. A partial explanation may be that in the former, a small number of policies are focused on relatively few actors (the suppliers) whereas in the latter many different policies and policy types are focused on many different actors (the consumers) – this issue is discussed in more general terms below. As an additional policy measure, the blending of HVOs may be targeted toward the suppliers, although the early nature of this fuel type requires further research into costing and feasibility.

4.2. Importance of Approach in this Paper

Studies on the dynamics of technology adoptaion have made a distinction between substitution and diffusion – the former referring to where new technology simply replaces existing technology, and the latter to where new technology creates new markets and where the existing technology continues to exist, albeit with a reduced niche share [41]. Ex-post analysis of policies to encourage new technologies have shown that policies where the new technology is a ready substitute for the incumbent have higher deployment rates than policies where the new technology has a greater degree of difference with the incumbent (e.g. the energy service provided by conventional cars is different in important ways with the energy service of electric cars which goes some way to explaining the latter’s limited deployment to-date). The greater the difference between the energy service of the new and existing technologies, the greater the uncertainty about the new technology’s rate of deployment. New technologies with greater differences, and thus greater uncertainty, are likely to need more policy attention.

This paper has shown that policy analysis with simulation models and ex-post analyses of similar policies are useful ways in beginning to lift the uncertainty about new technology diffusion. While there is still an uncertainty surrounding the direct effect one policy measure may have on new technology market share, the methodology presents the potential effect of a group of policy packages, providing an interface capable disaggregating these packages with further research into consumer behaviour. The method has outlined how technology pathways, optimised to least cost, can be complemented with simulation models of policy analysis that align with the least cost approaches but that provide additional understanding on the uncertainty in addition to ways to mitigate that uncertainty. Some technologies will require many policies to support their diffusion and some technologies will require few policies. This inequality between technology and policy has implications for modelling, since for technology optimization models, such as the Irish TIMES energy system model in this study, all technologies are equal when considering adoption, whereas in reality a suite of policies may be required for this adoption of one technology compared to another; simulation models, such as CarSTOCK, are capable of modelling such packages of policy measures. Furthermore, as energy systems models show more radically different energy decarbonisation scenarios (i.e. technologies that are less substitutable equivalents), there is a greater need for multi-modelling and policy analysis approach for all energy sectors.

4.3. Future Work and Research

This work has focused on the private car transport sector in Ireland. Modelling capacity already exists or is being developed to extend the work to other sectors (e.g. non-private car transport sector; residential sector, commercial sector). In addition, this work could be undertaken for more ambitious scenarios of overall mitigation potential than the 80% reduction explored in this paper since the recently ratified Paris Agreement is leading to questions being asked about the validity of an 80% reduction being in line with a “well below 2 degrees”. Further research could involve deepening the analysis with insights for modelling from literature on ex-post analysis of different policy types [42] and the literature on different policy mixes ([43]; [44]) and how they align with the transition pathways developed by the optimization models. A subsequent soft-link between an energy systems model and a dedicated power systems model would provide useful insights into the effect of electrification of the transport sector would have on the power systems, and would also aid in generating more accurate CO_2 emissions. There is also a certain need for further research into modelling methods capable of accurately capturing consumer behaviour in the transport sector, to aid associating the changes in market shares of vehicles following the introduction of purchasing incentives in a modelling framework.

5. Acknowledgments

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Figures

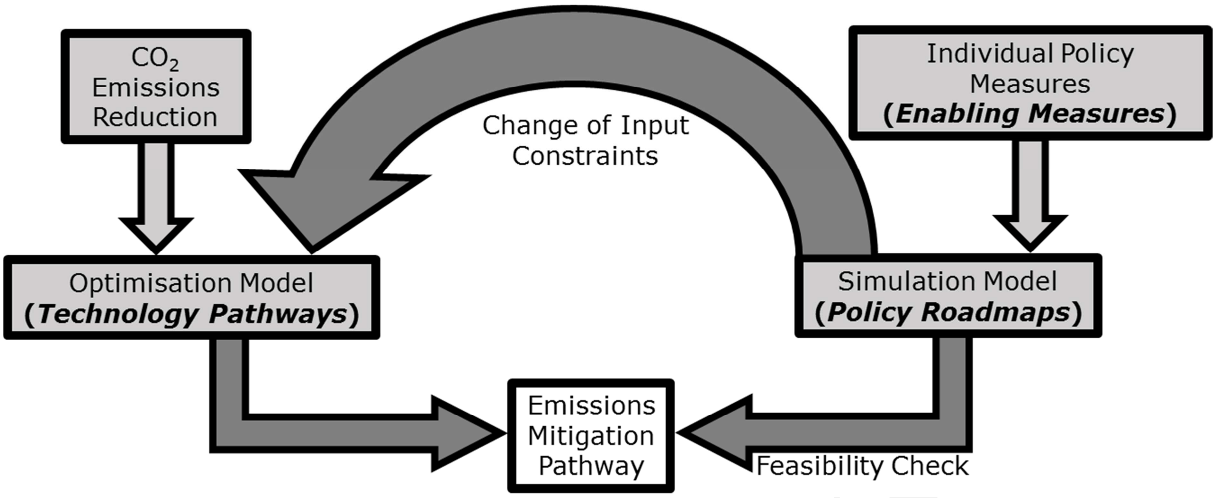


Figure 1: Method Flow Diagram

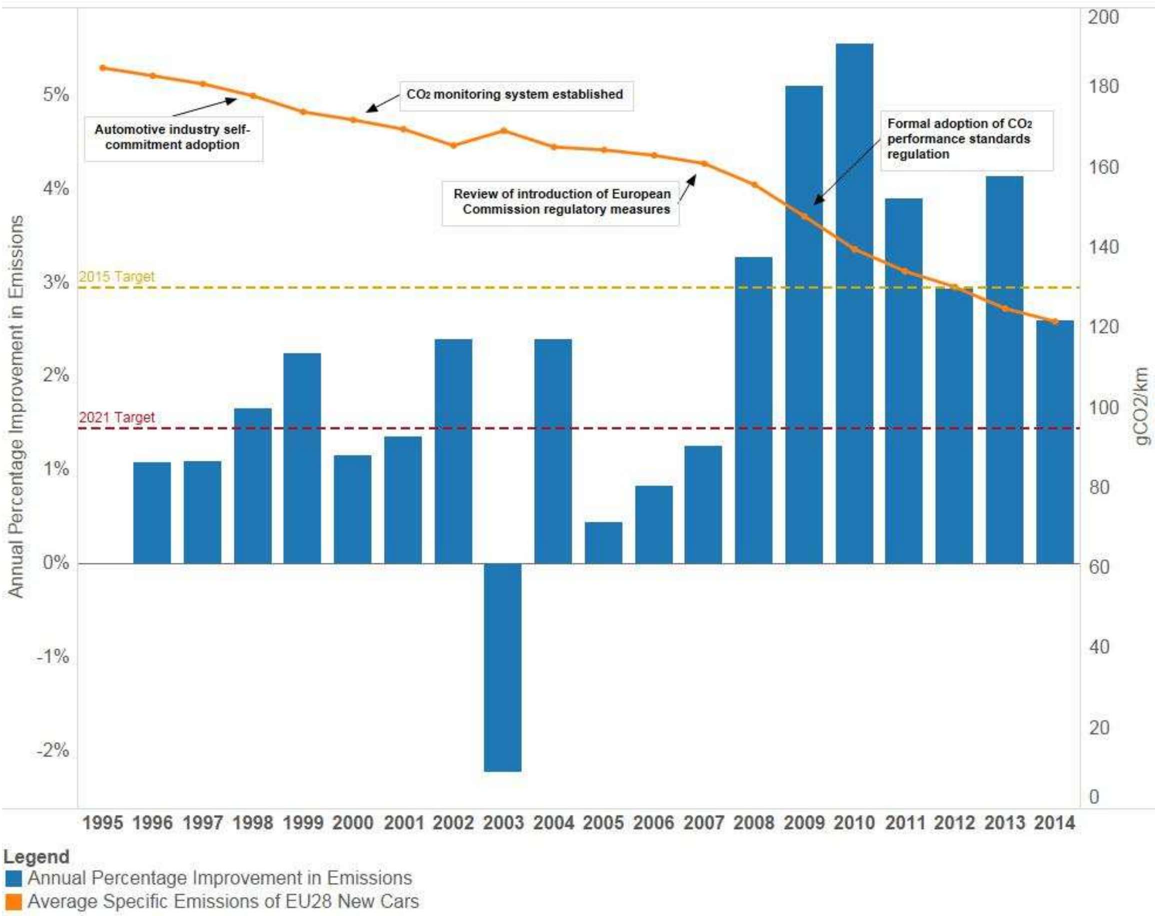


Figure 2: EU28 New Car Emissions in gCO_2/km (right) and Annual Percentage Improvement (left)

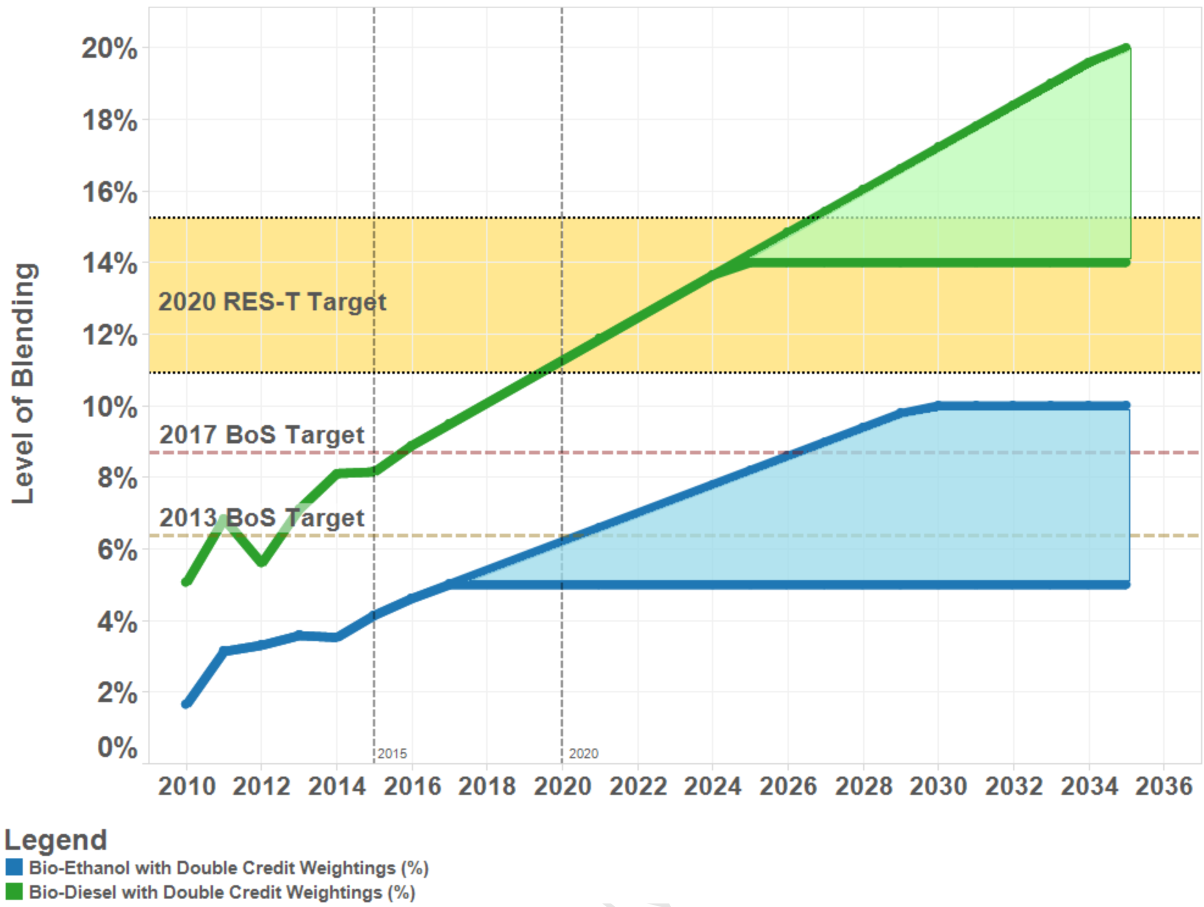


Figure 3: Historic and Projected Bio-Ethanol and Bio-Diesel Blending by Volume in Ireland[4] *[37]*

[4] Article 21 of the RED allows for double weightings counted towards biofuels produced from wastes, residues, non-food cellulosic material, and ligno-cellulosic material [45]. This figure only considers the weighted value.

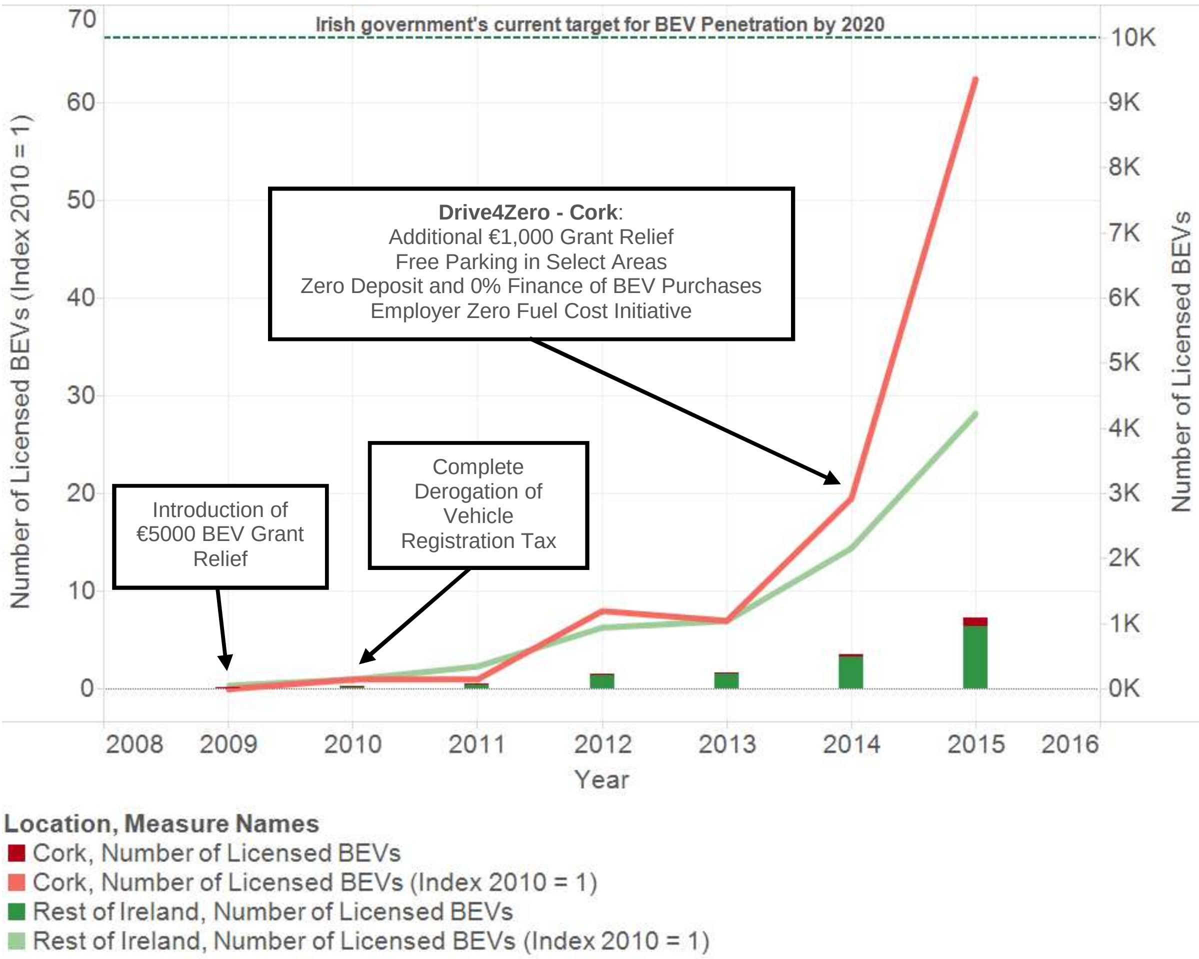
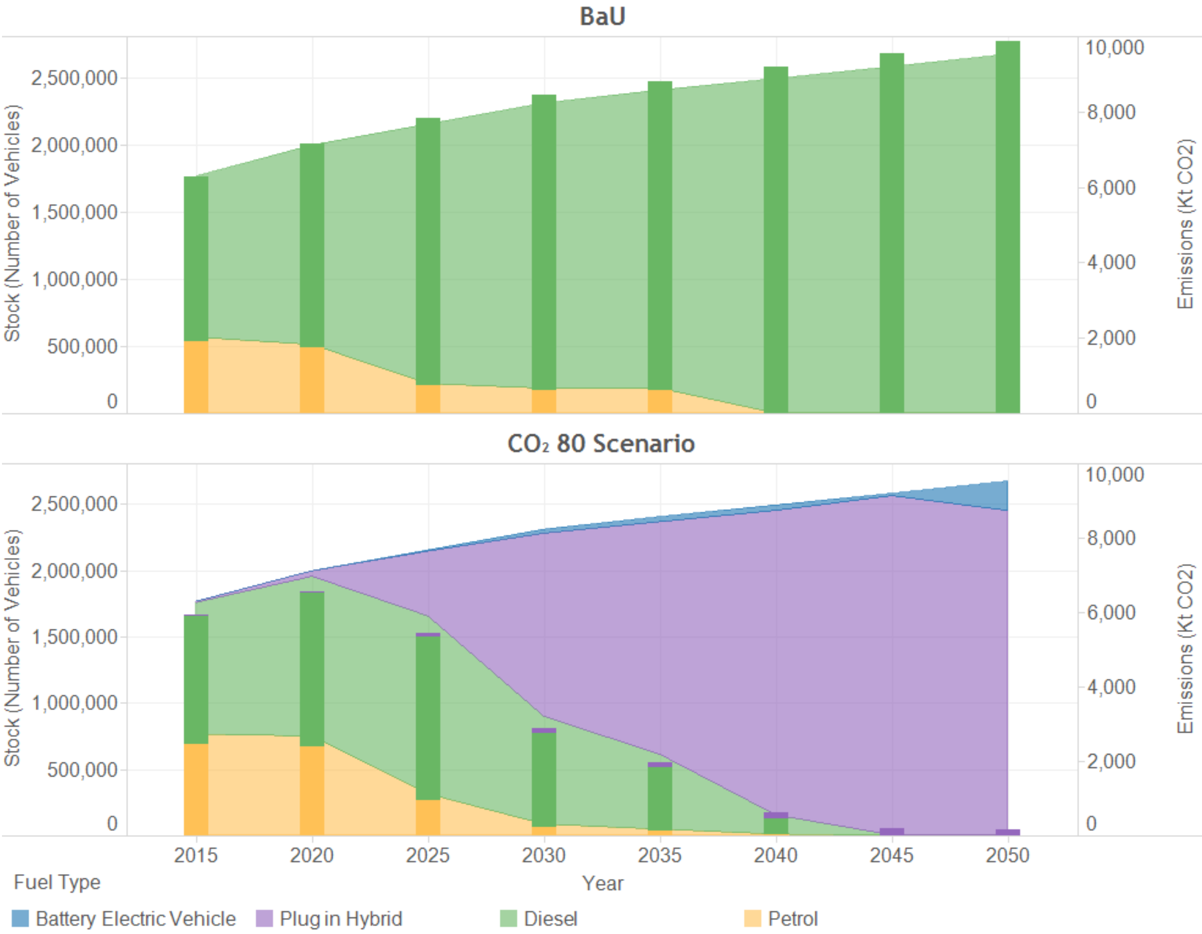


Figure 4: Number of licensed BEVs in Cork and rest of Ireland in total (bar charts, right axis) and indexed (line, left axis) form



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617 ***Figure 5.*** *Evolution of Private Car Emissions (Bar Charts) and Stock (Area Chart) over Time*

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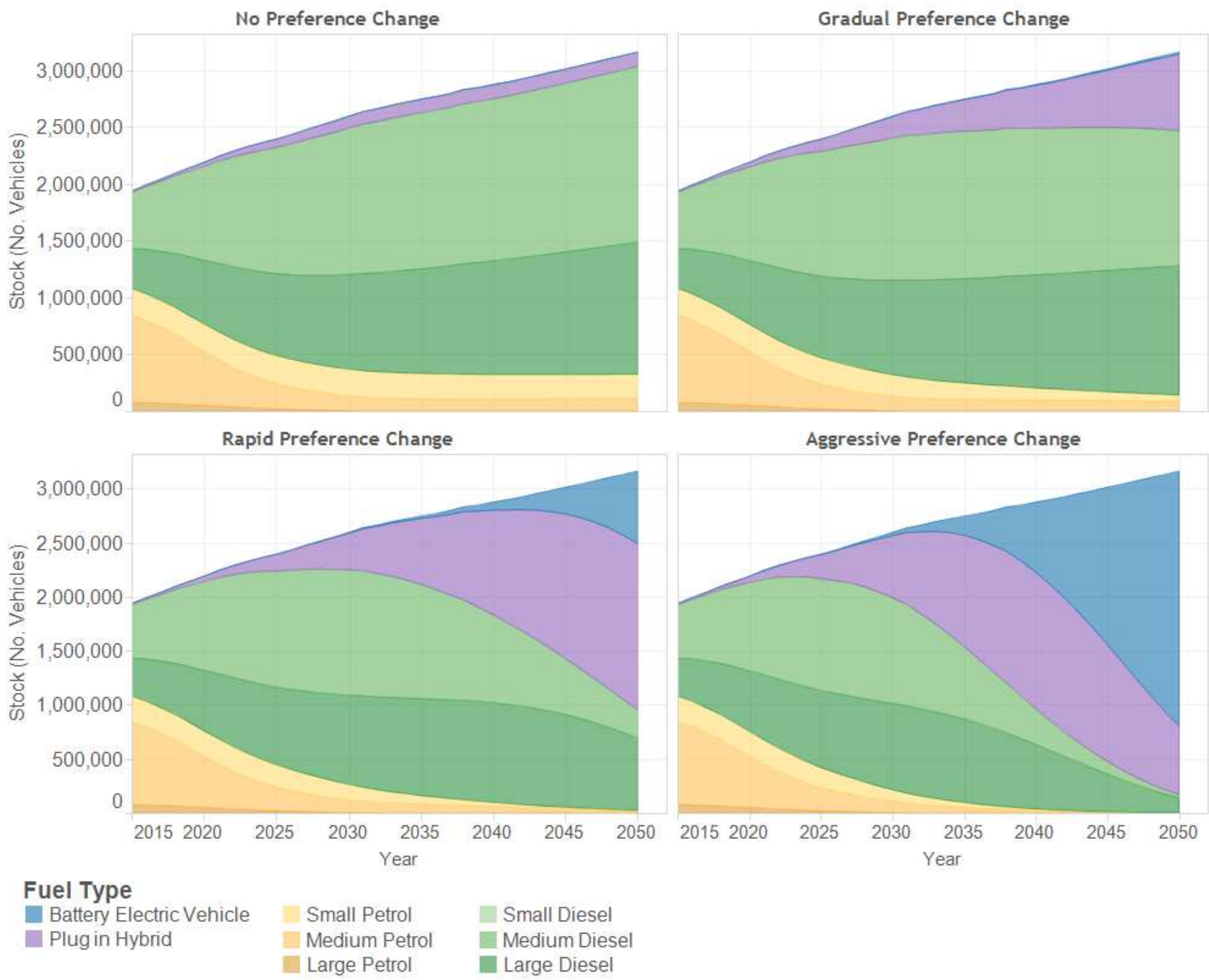

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620 *Figure 6: Private Car Stock profiles under Varying Preference Scenarios*

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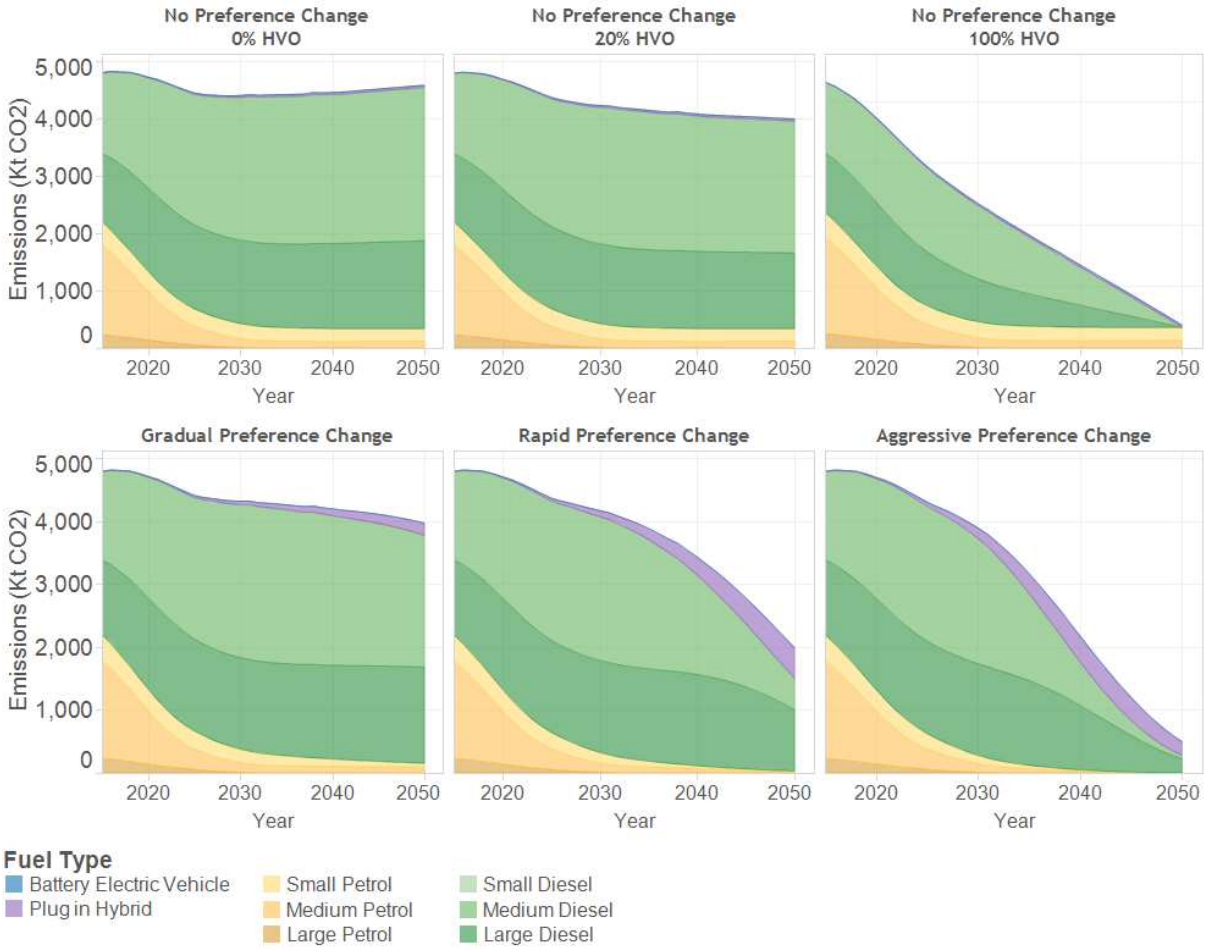

Figure 7: CO_2 Emission profiles under varying preference scenarios

Tables

Table 1: Discrete Choice Model assumptions used to calculate market share constraints in Irish TIMES

Technology	2015				2050			
	CC	MC	EC	i	CC	MC	EC	i
Petrol Car	€28,316	€5,598	1.26 c/ltr	-	€28,316	€5,598	1.66 c/ltr	-
Diesel Car	€28,316	€5,598	1.19 c/ltr	-	€28,316	€5,598	1.57 c/ltr	-
BEV	€21,490*	€5,505	0.13 c/kWh	€29,241	€10,041*	€5,505	0.13 c/kWh	€3,843
PHEV	€31,450**	€5,455	0.81 c/ltr	€10,542	€14,695**	€5,455	1.05 c/ltr	-

* Price includes government grant of €5,000 towards Pure Electric Vehicle purchasing
** Price includes government grant of €2,500 towards Plug in Hybrid Electric Vehicle purchasing

Table 2: Multi-Model Approach

Model	Approach	Output
Irish TIMES	Optimisation	Technology Pathway
CarSTOCK	Simulation	Policy Roadmap
-	Ex-post & ex-ante analysis	Enabling Policies

Table 3: Flow of Technology Pathways to Enabling Measures

Technology Pathway	Reduced Fuel Intensive Use	Increased Biofuels Use	Increased EVs Penetration
Policy Roadmap	Efficiency Improvements	Renewable Transport Targets	Electrification of Transport
Enabling Measures	CO_2 Regulation + Car Tax	Biofuel Obligation Scheme	Incentives to Shift Preference

Highlights

- We create an integrated energy technology & policy analysis of Ireland's LDV sector
- A multi-model approach is combined with an ex-post and ex-ante analysis of policies
- Results identify technology pathways, policy roadmaps and specific policy measures
- Efficiency measures and biofuel blending alone provide an 18% decarbonisation
- Electric vehicles or drop-in biofuels are needed for 95% decarbonisation by 2050