Top-down and bottom-up policy evaluation – a multi-model approach

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Abstract

This paper describes a multi-model approach to evaluating energy efficiency policies and uses it to assess energy efficiency options in car transport. The methodology comprises a soft-linking mechanism between two bottom-up techno-economic modelling tools, i) a full energy systems optimisation model and ii) a car stock simulation model. The energy systems model is used to inform energy efficiency targets for car transport over the period to 2050, using top-down policy evaluation, informing in essence a technology roadmap for car transport. This is done by providing energy system pathways to meet future energy needs at least cost and constrained by a maximum level of CO_2 emissions. The simulation model then assesses this technology roadmap using higher temporal (annual) resolution, increased detail on individual car technologies and by adding a bottom-up assessment of policy measures. Through use of additional detail, the simulation model is able to use scenario analysis to evaluate particular aspects of the implementation of a policy, such as varying implementation rates and the interaction effect, and can provide insight into which policies are effective. The purpose of this paper is to illustrate how this multi-model approach can be used to generate technology roadmaps (to inform targets) and add value to this by also exploring policy roadmaps to deliver the technology goals. The paper applies this methodology to a single Member State, Ireland.

Introduction

Ireland faces very challenging short term emissions reductions targets for 2020 (Chiodi, et al., 2013) and preliminary discussions are currently underway regarding targets for 2030 (Department of Communications, Energy and Natural Resources, 2014) (Chiodi, Deane, Cahill, Gargiulo, & Ó Gallachóir, 2014). One element of the European Council conclusions (European Council, 2014) in October 2014 on the 2030 energy and climate policy framework, was a call for countries to set ambitious targets and policies:

> The European Council calls on all countries to come forward with ambitious targets and policies well in advance of the Conference of the Parties 21 in Paris.

There is a clear and urgent need for useful methods for effective planning and for informing the implementation of policy measures. Least-cost optimisation models are currently used in generating the optimal technology pathways for an energy system for a given constraint, such as a greenhouse gas (GHG) emission reduction (Yang, Yeh, Zakerinia, Ramea, & McCollum, 2015). These analyses may be made specific for a local, national or multi-regional model (Chiodi, et al., 2012) (Vaillancourt, et al., 2014). Models are generally used in the analysis of a full energy system, however they may also be used more specifically for the analysis of various sectors in the energy system (e.g. the private car fleet, residential heating) (Fehrenbach, Merkel, McKenna, Karl, & Fichtner, 2014). Energy service demands are generally calculated exogenously for each sector and entered into the system, e.g. as passenger kilometres for the private transport sector. Using these energy service demands as an input, a least-cost optimisation model is capable of determining what is required in terms of efficiency improvement in each of these sectors given an over-arching constraint. One problem encountered with this method in determining the required level of energy efficiency improvement in an energy system is that there is no strong indicator of which policies would optimally achieve these targets, how policy performance is aligned with these targets and whether these targets are realistic (Arvesen, Bright, & Hertwich, 2011).

Combining full energy systems models with sectoral modelling approaches may help overcome these challenges and has been used previously to add insights to the power system results from energy systems modelling scenario analysis (Deane, Chiodi, Gargiulo, & Ó Gallachoir, 2012) (Deane, Gracceva, Chiodi, Gargiulo, & Ó Gallachóir, 2015) (Deane J. , et al., 2013). A multi-model approach has also been utilised to soft link an energy systems model and an agricultural model to explore mitigation across the full economy (Chiodi, et al.). This multi-model approach allows for the informing of policy measures, which may be implemented in reaching the targets outlined by a least-cost optimisation model. This is due to the much higher level of temporal and technical detail in one specific sector in a sectoral simulation model compared to the level of detail in the optimisation model, which may not be of a high enough level of detail to be feasible. This multi-model approach could also be characterised as a multi-scenario analysis approach, with the energy systems model having a normative scenario type approach, and the sectoral model having an exploratory scenario type approach (Carter et al., 2001).

A note on the precise meaning of some terms used throughout this paper: The terms top-down and bottom-up can mean different things in different contexts. In an energy systems modelling context, the terms refer to the differences between an econometric type approach (top-down) and an engineering technology type approach (bottom-up); both models in this paper are based on bottom-up technology based approaches, though they differ in the level of detail employed. In the context of policy evaluation, top-down refers to the imposition of targets, whereas bottom-up refers to evaluation at a measure-by-measure level. For example, top-down policy evaluation could involve modelling based off an overarching CO_2 emissions reduction for some target year, or over a time horizon, and calculating the optimum effort required per sector. On the other hand, bottom-up policy evaluation could create scenarios based off the lower end of sectors, e.g. establishing a capital grant scheme for electric heating systems and setting a target of 10 % of all houses in a country to have electric heating for a given year, and analysing how this effects the overall energy system over a given period. In a strict sense, the term policy evaluation refers to measurement, reporting and verification (MRV) and is an ex-post activity, i.e. the performance of a particular policy-measure is evaluated after data has been gathered on its performance. In this paper, policy evaluation is used in a more general sense to refer to how effectively a suite of policy-measures can achieve a top-down target and it is in this context that the analysis presented combines a bottom-up and top-down approach. In contrast to the MRV approach to policy evaluation, this approach is an ex-ante activity, i.e. the policy hasn't been implemented yet, but it is being evaluated for how much it is likely to be able to contribute to the overall target.

This paper presents a soft-linking methodology between the Irish TIMES model (Chiodi, et al., 2012) – a least-cost optimisation model of the Irish energy system – and the CarSTOCK model (Daly & Ó Gallachóir, March 2011) (Daly & Ó Gallachóir, 2012) – a sectoral simulation model of the private transport sector in Ireland. A focus is given to the private transport sector as the transport sector currently consumes the most energy in Ireland relative to any other sector (40 % of total final energy demand of all sectors in Ireland) with the private car fleet being the most energy consuming form of transport in the country (43 % share of transport energy demand by mode in 2013 (Dineen, Howley, & Holland, 2014)).

The timelines and time resolution of a simulation model are more aligned with how (in reality) a policy measure will be implemented, i.e. a particular measure will have a lifetime of a number of years, with typically a phase-in period forming part of that lifetime. An energy systems model such as TIMES is not designed for such zoomed in analysis on such short time slices, i.e. it typically solves system modelling problems in time periods of five years. A target may be feasible in a technology sense, but infeasible in an implementation sense, and the manner in which this is addressed in TIMES is via hurdle rates for technology changeover.

This paper explores an ambitious long term scenario based upon the European Union Commission's recommended GHG emissions reduction by 2050 of 80 %–95 % relative to 1990 (European Commission, 2011). An 80 % CO_2 emissions reduction by 2050 relative to 1990 constraint is entered into the Irish TIMES model which determines the least-cost solution in all sectors of the economy (agriculture, residential, commercial, industry and transport). This Scenario would require a total reduction in CO_2 emissions in Ireland of 36,205 Mt CO_2 by 2050 relative to 2010. A number of scenarios are created in the CarSTOCK model to scrutinise the results from the private transport fleet in the Irish TIMES model. This allows for insight and evaluation of which policy measures may be taken to meet the results in the private transport fleet as laid out by the Irish TIMES model as well as the analysis of whether the results in the private transport fleet in the TIMES are actually feasible through a multi-model approach. If the results are not feasible, a new constraint may have to be placed in the Irish TIMES model to create a more realistic scenario.

This paper is organised as follows: the first section below outlines the methodology approach used, looking specifically at the technology roadmap as generated by the least cost optimization model (Irish TIMES), the policy roadmap as generated by the sectoral simulation model (CarSTOCK) and the combined effort of the top-down and bottom-up models to evaluate policy implementation. The results section presents the set of results for each of the steps explained above in the methodology used. The discussion sections highlights the key findings of the results. The final section concludes.

Methodology – Multi-Model Approach

The methodology is divided into 3 sections; (1) Technology Roadmaps, which is the preliminary running of the Irish TIMES model to analyse the technology requirements (specifically in the private car sector) to meet the 80 % CO_2 reduction by 2050 relative to 1990; (2) Policy Roadmaps, which assesses the feasibility of the results of the private car sector in the Irish TIMES model using the CarSTOCK model; (3) Evaluating

Technology and Policy Feasibility, which changes the input constraints on the Irish TIMES model following the feasibility evaluation and re-runs the model.

1. TECHNOLOGY ROADMAPS (IRISH TIMES MODEL)

The Irish TIMES model is a linear optimisation model with an objective function to minimise total system cost (maximizes the total discounted surplus) subject to imposed constraints for the Irish energy system. Mathematical equations describe the relationships and interaction between the many technologies, drivers and commodities in the Irish TIMES model. 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. The model adopts a system planner perspective, seeking out least cost solution over the entire time horizon under scrutiny. This allows competition between technologies and fuels across the full energy system (hence electricity generated by fossil fuels and renewable energy competes with liquid and gaseous fuels to deliver exogenously calculated passenger kilometre projections. The model has perfect foresight and *knows* what the future demand for passenger and freight transport will be. When deciding between technologies, it takes into account residual capacity (e.g. existing cars on the road), their fuel, operational, and maintenance costs and compares them with new technologies that require capital investment costs but generally have improved efficiencies and lower emissions. Generally the model is run in the absence of policy constraints and then re-run with a constraint (e.g. maximum level of CO_2 emissions). The outputs include the costs, level of efficiency required and fuel switching in each sector to achieve this constraint at least cost. The Irish TIMES model was derived from the Pan European TIMES model which was developed as a multi-regional TIMES model. The individual sectors were then updated using extensive local knowledge to create an Irish specific model.

Constraint on Greenhouse Gas Emissions

An assessment report released from the Inter-Governmental Panel on Climate Change (IPCC) summarised that the cause for increase in global surface temperature over the last twelve years is very likely due to the increase in GHG concentrations (IPCC, 2007a). These 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. An 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 (IPCC, 2007b). The EU has determined that in meeting this target, industrialised countries should contribute more than a 50 % reduction and have advised an 80 % to 95 % reduction by 2050 relative to 1990.

The top down scenario informing this paper deals with a reduction in CO_2 emissions of 80 % by 2050 relative to 1990: this is entered as a constraint for the Irish TIMES model which determines an optimal technology pathway to meet this target by 2050. The results for this scenario detail what is required in all sectors of the economy in terms of CO_2 emissions reductions. Within each of these sectors, Irish TIMES disaggregates into sub-sectors and details the level of effort required in each of these sectors of the energy system.

Private Car Fleet Projections

Following the application of a constraint to the energy system in Ireland, the Irish TIMES model calculates the level of efficiency improvement required in the private transport sector to contribute to this overall target. The model disaggregates the private car fleet into fuel type, vintage and number of vehicles as well as the total energy and emissions from the respective fuel types. Unlike the CarSTOCK model, vehicles are not currently disaggregated by engine size in Irish TIMES and there is no reduction in the mileage over the lifetime of the vehicle.

2. POLICY ROADMAPS (CARSTOCK MODEL)

The CarSTOCK model is a sectoral simulation model of the private transport fleet in Ireland that projects the evolution of the private car fleet, energy use and related CO_2 emissions out to 2050. CarSTOCK was developed in 2008, when transport in energy accounted for 43 % of the total final energy demand and had experienced an increase of 277 % relative to 1990 (Howley, Dennehy, & Ó Gallachóir, 2009). To achieve a reduction in the overall CO_2 emissions in Ireland of 80 % by 2050 relative to 1990, it is clear that a significant amount of efficiency improvements are required in the private transport sector.

The CarSTOCK model was built using fleet structure, the profile of activity, and fleet efficiency as explanatory variables. A database of the historic private car fleet from 2000 to 2008 was sourced locally which was used to project the explanatory variables forward to 2050. The drivers of the private car fleet used are GNP and fuel price which were projected exogenously from the model by the Economic Social Research Institute (ESRI) and the European Commission respectively. The model uses a combination of income and fuel elasticities of demand to calculate the total level of sales, stock and vehicle kilometres in the country per annum. A survival profile is used to determine the scrappage rates of vehicles per year. The car stock data is disaggregated annually by vintage, fuel type and engine size. This level of detail is much higher compared to the transport sector in the Irish TIMES model which currently only disaggregates by fuel type and uses five yearly time steps. This results in a much more detailed evolution of the private car fleet, which is much more effective at giving an insight to the policies which may allow for the reduction of CO_2 emissions in this sector and assess the feasibility of the results from Irish TIMES.

The efficiency improvements may be implemented in the form of policies on privately owned vehicles. For example, in 2008 there was a change in the method of taxation on motor vehicles, which went from being based on the size of a vehicle's engine to being based on the level of emissions from the vehicle. This change resulted in a significant migration in the private car fleet to more efficient vehicles (Rogan, Dennehy, Daly, Howley, & Ó Gallachóir, 2011). Policies may also be implemented in the form of a maximum threshold on the average levels of specific emissions for the new car stock, for example the EC regulation No. 443/2009 makes it a requirement for all new cars in Ireland purchased from 2020 onwards to have an average emissions level of 95 gCO_2/km (The European Parliment and The Council of The European Union, 2009). The percentage share of car sales by fuel type can also be altered in the model, which allows for a specific level of penetration of renewable vehicles such as Electric Vehicles (EVs). These individual policies may not necessarily be the best methods of achieving the CO_2 reduction targets set out for the country or even realistically achievable (as is demonstrated in the 95 gCO_2/km scenario below), however by simulating scenarios which may complement these policies, an idea of the most effective policy measures may become more evident.

The technology roadmaps from Irish TIMES are used to develop preliminary scenarios in the CarSTOCK model in order to simulate the effects of policies in the long-term. These scenarios may then be combined to show the interaction effect between each of the policies to understand the action required in the private transport sector to meet significant levels of emissions reductions and compare these with those arrived at in decarbonisation scenario results from the Irish TIMES model. The Irish TIMES scenario has a policy constraint imposed on it of an 80 % CO_2 emissions reduction over the entire energy systems by 2050 relative to 1990. The scenarios developed in the CarSTOCK model are designed to demonstrate the level of difficulty in meeting the TIMES decarbonisation results as well as to provide insights into a range of policy measures that may allow for the decarbonisation of the private car fleet in Ireland.

Implementation of Policies

The CarSTOCK scenarios developed from the technology pathways of the private transport sector in the 80% CO_2 emissions reduction scenario in the Irish TIMES model are described in the section.

BaU

The business as usual (BaU) scenario forms the base of all scenarios dealt with in this section. The total car stock and new car sales are projected forward using the drivers of Gross National Product (GNP) and fuel price. GNP is projected exogenously using a macro-economic model specific to Ireland (Bergin, Conefrey, Fitzgerald, Kearney, & Žnuderl, 2013). Fuel price is projected forward exogenously by the European Commission (Capros, et al., 2013). These drivers are used with fuel price elasticities of demand and income elasticities of demand. The projection of the total car stock is also a function of the change in average mileage in cars, which is linearly projected using past historic data. The CarSTOCK model projects forward stock, sales, average mileage, specific energy consumption (SEC), energy and emissions to 2050. All of these variables are disaggregated by fuel type, engine size and vintage for this scenario and every scenario hereafter.

The BaU scenario looks at the evolution of the structure and activity of the private car fleet as if there are no policies implemented resulting in no switch to more efficient vehicles or reduction in passenger kilometres. This scenario is not intended to be realistic, but is used to quantify the impact of an energy efficiency improvement which is dealt with in the following scenarios.

95 g CO_2/km

The 95 g CO_2/km deals with a migration away from low-grade efficient vehicles towards a more efficient private car fleet. The constraint imposed here looks at a linear progression of the efficiency of new cars tending towards an average maximum specific emissions level of 130 g CO_2/km by 2015 95 g CO_2/km by 2020. This is in keeping with EC regulation No. 443/2009 (The European Parliment and The Council of The European Union, 2009). The SEC of the private car fleet is then held constant at the 2020 levels.

130 g CO_2/km

Research carried out by the EU commission focused on the potential CO_2 reduction from vehicle technology improvement up to 2050 which assumed a technology improvement of 1.3 % for all gasoline and diesel cars up to 2020 and 0.5 % thereafter (Pasaoglu, Honselaar, & Thiel, 2011). This same assumption was applied to the SEC of all new cars in the CarSTOCK model leading up to 2050 to have a migration away from vehicles whose carbon emissions lie in the lower end of the carbon band. This assumption led to a total specific average vehicle emissions level of 130 g CO_2/km by 2020. This assumption was seen to be more realistic than the previous 95 g CO_2/km scenario and was therefore used in all subsequent scenarios. Anecdotal evidence suggests that while cars are achieving the emissions performance targets under test conditions, the difference between *test* emissions performance and *on-road* emissions performance is growing (Mock, et al., September 2014).

130 g CO_2/km + SmTr

A number of non-technological targets were set out in the Smarter Travel document released by the department of transport which deals with some ambitious plans for modal switching within the Irish private transport fleet (Department of Transport, 2009). This considers a shift in the use of private vehicles towards public transport which results in a cap being placed on the total passenger kilometres from 2016 onwards in the private fleet and contributes to an overall reduction in the CO_2 emissions in the transport sectors. This new technology shift is used in conjunction with the efficiency improvement outlined in the previous scenario.

130 g CO_2/km + SmTr + eco

A second technology measure is accounted for in this scenario where the installation of a gearshift indicator is made on all new cars by 2013. This results in a 1.5 % energy saving on all cars from this year onwards which is implemented through the reduction of the SEC of the previous scenario by 1.5 % from the year 2013 onwards. A technical report assigned by the European Commission determined that this could result in a 3 % energy saving (Smokers, et al., 2006).

130 g CO_2/km + SmTr + eco + EV

This final scenario was created in conjunction with the previous scenario with the extra added measure of the penetration of electric vehicles into the market. There is a linear increase in the percentage technology sales share between 2014 and 2030 where all new car sales by 2030 onwards are assumed to of electric vehicles. This assumption results in the steady removal of petrol and diesel fuelled vehicles from the private car fleet and the penetration of more electric vehicles. In 2008 new electric vehicles are assumed to have a SEC of 28 kWh/100 km which is the equivalent of 1 MJ/km (Thomas, 2009). A technology improvement is assumed in the CarSTOCK model such that by 2050 the SEC of electric vehicles are the same as the Irish TIMES model at a value of 0.51 MJ/km. The emissions factor used for electricity generation was 135.7 tCO_2/TJ based on the year 2013 (Dineen, Howley, & Holland, 2014) while the projected values of renewable energy share of electricity (RES-E) in Ireland were taken from the Irish TIMES model from a scenario which had a value of 84 % RES-E by 2050. Ireland already had a RES-E level of 20 % in 2013 so the total emissions factor for electricity generation in 2050 using a RES-E of 84 % was 21.7 tCO_2/TJ.

3. EVALUATING TECHNOLOGY AND POLICY FEASIBILITY (MULTI-MODEL APPROACH)

In a case where the results of the least-cost optimisation model are deemed to be difficult to achieve based on the results of the CarSTOCK model (as is the case in this example, described in further detail in the results section) a multi-model approach may be adopted, which soft-links both models. If the original results of the least-cost optimisation model are seen to be unfeasible, a new constraint may be required in order to provide more realistic targets for the future. Following the analysis of the results of the Irish TIMES model used in this example, two possibilities ensue:

- The results of the private transport sector in Irish TIMES are met in the CarSTOCK model rendering the scenario to be acceptable and informing policies which may be implemented to achieve these results.
- The results of the private transport sector in Irish TIMES are not met in the CarSTOCK model rendering the scenario to be infeasible.

In the latter case, even though the model results are not met, the model still provides insights into the policies, which result in the closest match. If we do not envisage implementing further policies in the sectoral simulation model (such as incentivising the scrappage of petrol and diesel cars or increasing the efficiency of new cars any further) then it would be necessary to change the constraints on the Irish TIMES model to satisfy the results of the sectoral simulation model. Failing to do this may result in a struggle to follow an infeasible target laid down by the Irish TIMES model and hence the inability to meet an overarching target such as the CO_2 emissions reduction in Ireland of 80 % by 2050 relative to 1990. By changing the input constraints on the private transport sector in the Irish TIMES model, other areas in the energy system may be able compensate for this newly imposed constraint on the transport sector. This allows for the recalculation of more feasible results for the same scenario while still informing on the policy measures which may be taken in achieving these results. In this case, by limiting the emissions reduction potential of the private transport sector, the Irish TIMES model is capable of calculating which sectors in the model can compensate for this limiting. This may give a more realistic approach to achieving emissions reduction whereby the unfeasibility of one sector is analysed and compensated in other sectors. The flow of the multi-model approach is outlined below in Figure 1.

Due to the lower level of private transport data in the Irish TIMES model relative to the CarSTOCK model, a check on the difficulty of meeting targets is carried out through implementing a new constraint to the Irish TIMES model. This constraint is made to match the results of the 130 g CO_2/km + SmTr + eco + EV CarSTOCK scenario to determine whether this new constraint is realistically achievable according to the Irish TIMES 80 % CO_2 reduction scenario. This required a new input constraint on the level of electric vehicle penetration to be set at 82 % by 2050, which differs from the 100 % penetration in the original 80 % CO_2 reduction scenario in the Irish TIMES model.

Results

This sections presents the evolution of the private car fleet in the Irish TIMES model in terms of stock, SEC and specific emissions due the imposition of an 80 % CO_2 emissions reduction by 2050 relative to 1990. The evolution of the private car fleet in the CarSTOCK model following the introduction of the scenarios described above, which attempt to match the results of the Irish TIMES 80 % CO_2 emissions reduction scenario, is also presented. A comparison is then drawn up between the two results scrutinising the feasibility of the Irish TIMES results. Finally the results from the re-run of the Irish TIMES model with the new imposed constraint following the feasibility analysis of the CarSTOCK model are presented.

Similar to the methodology section, the results are broken down into 3 sections; (1) Technology Roadmaps, the preliminary results using the Irish TIMES model; (2) Policy Feasibility, the results of the feasibility analysis using the CarSTOCK model; (3) Evaluating Technology and Policy Feasibility, the results from the Irish TIMES model with the new input constraint based on the feasibility analysis from the CarSTOCK model.

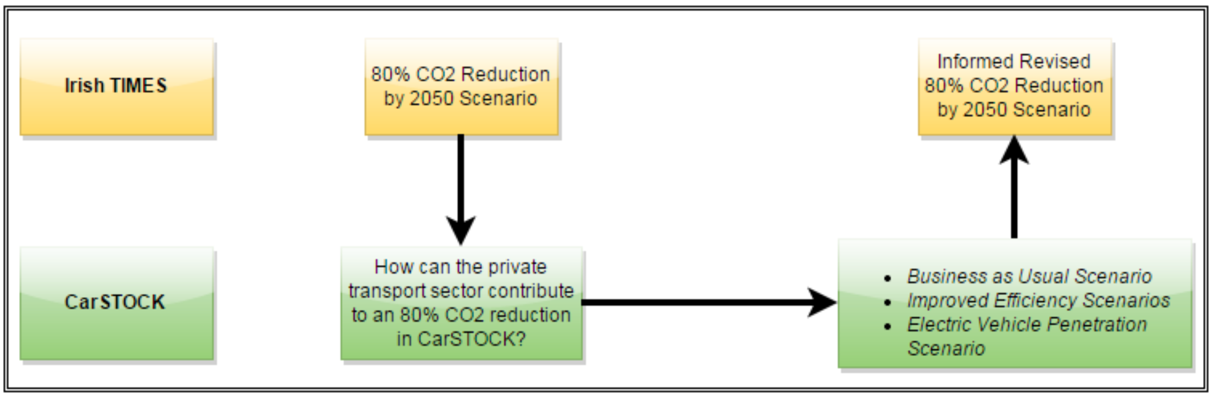

Figure 1. Methodology Flow Diagram.

1. TECHNOLOGY ROADMAPS (IRISH TIMES MODEL)

Within the 80 % CO_2 emissions reduction scenario for 2050 relative to 1990 imposed on the entire energy system, the Irish TIMES model calculated a 97.3 % reduction of CO_2 emissions in the private transport sector. The private car sector is initially dominated by diesel and petrol cars up to 2030. There is a sudden penetration of electric vehicles in 2030 with 1,070,000 plug-in Hybrids emerging into the system while petrol fuelled cars become completely excluded by this year. By 2050 there are only electric vehicles in the country with 2,450,000 PEVs and 223,000 battery electric vehicles. The evolution of the car fleet can be seen below in Figure 2. There is an upward trend in the overall fleet with a considerable mitigation away from diesel and petrol cars towards renewable vehicles from 2030 onwards.

The emergence of electric vehicles into the system by 2030 in the Irish TIMES scenario results in a significant drop of nearly 1 MJ/km between 2025 and 2030 and a further 1 MJ/km reduction between 2030 and 2050. The overall SEC drops from 2.77 MJ/km to 0.55 MJ/km between 2010 and 2050.

Private Car Fleet Emissions

Following the significant introduction of EVs into the car fleet by 2030, there is a huge reduction in the CO_2 emissions in the private transport fleet resulting in the overall 97 % reduction in the CO_2 levels in the private car fleet in the system.

A significant drop is seen in the gCO_2/km between 2025 and 2030 in the Irish TIMES model due to the emergence of EVs. By 2050 there is an average level of 3.49 g CO_2/km in the private car fleet which is a 98.1 % reduction in the specific emissions by 2050 relative to 2010. Comparatively, there is an 82 % reduction in the Car STOCK scenario by 2050 relative to 2010.

2. POLICY ROADMAPS (CARSTOCK MODEL)

The first scenario which was analysed was the BaU which had an overall 8 % increase in CO_2 emissions in the private car fleet by 2050 relative to 2008, reaching approximately 6,200 kt CO_2.The results from this scenario were used as a baseline for the effects of efficiency improvement in all subsequent scenarios.

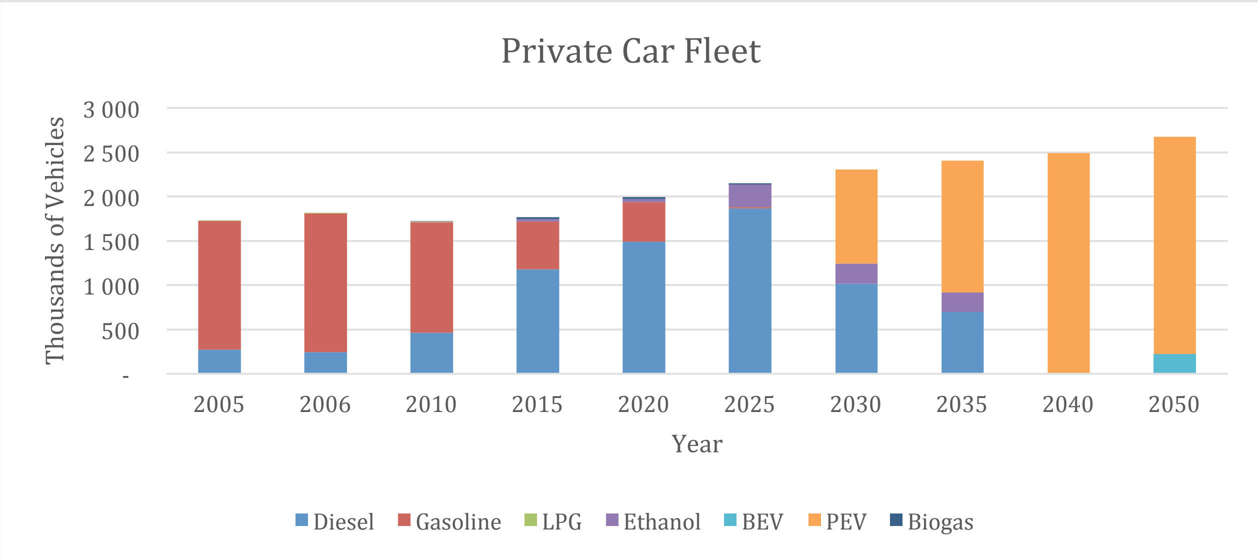

Figure 2. Evolution of the Car Fleet over Time in Irish TIMES Decarbonisation Scenario.

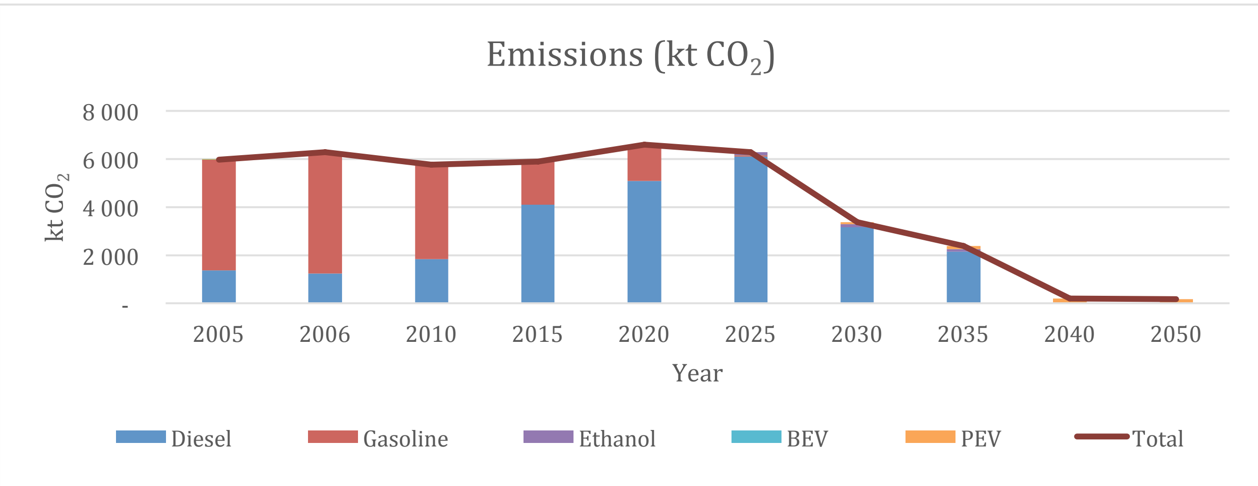

Figure 3. Evolution of Private Car Emissions over Time

Table 1. Comparison of SECs in Irish TIMES and CarSTOCK Scenarios.

SEC Comparison Active Unit: MJ/km	2010	2015	2020	2025	2030	2035	2040	2050
TIMES 80 % CO_2 Reduction	2.77	2.62	2.58	2.44	1.56	1.27	0.59	0.55
BaU + 130 g + SmTr + eco + EV	2.45	2.33	2.08	1.80	1.52	1.26	1.05	0.72

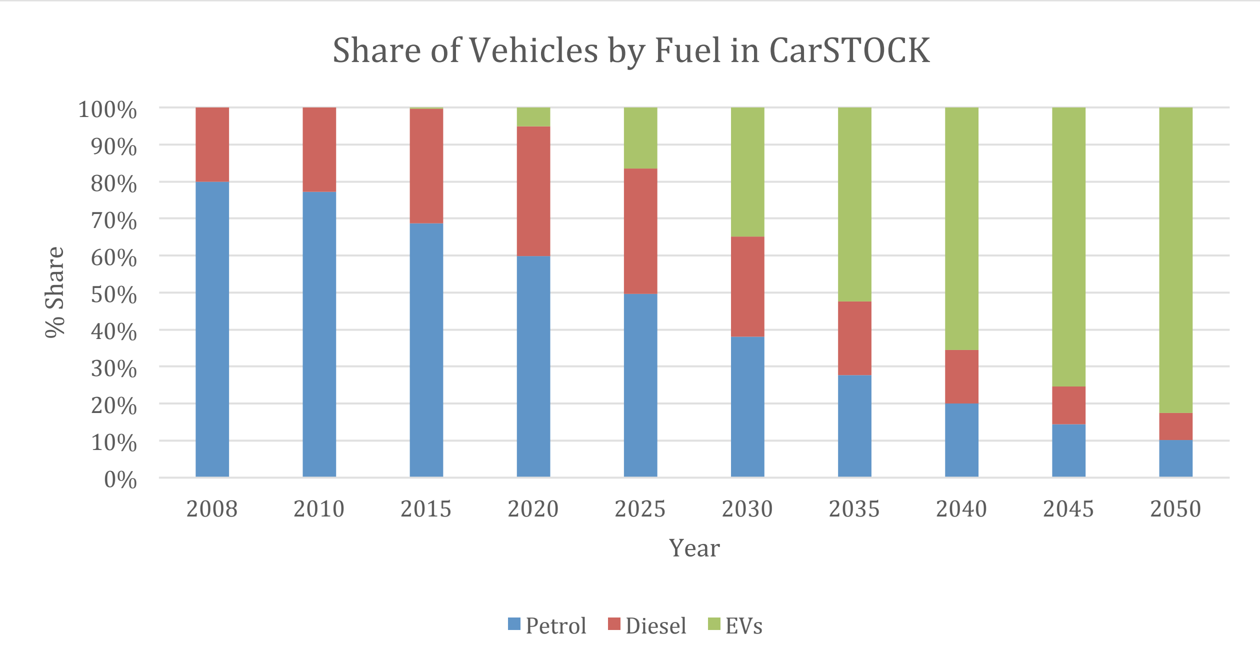

Figure 4. Percentage Share of Stock by Fuel Type in Final CarSTOCK Scenario.

The BaU + 95 g scenario, which saw the efficiencies of all new private cars averaging 95 g CO_2/km by 2020, achieved a 19 % reduction by 2050 relative to 2008. Even though this target was in keeping with EC regulation No. 443/2009, the level of technology improvement which would be required to reach this level is not in accordance with the research carried out by the EU Commission (Pasaoglu, Honselaar, & Thiel, 2011). Therefore this scenario was ruled out to be unfeasible and focus was placed on the 130 g CO_2/km scenario which had a much lower emissions reduction of 3 %. This scenario was considered more realistic and therefore used as a baseline for the following scenarios.

The introduction of smarter travel within the Irish private transport fleet saw a considerable reduction in total vehicles and average annual mileage relative to the previous scenario. The average annual mileage was held constant at 2016 levels at 32,801 km. This resulted in a total reduction in the car fleet of 27 % by 2050 relative to the 130 g CO_2/km scenario. This new constraint resulted in a total final reduction in CO_2 emissions of 30 % by 2050 relative to 2008. The addition of the gearshift indicator in all new vehicles by 2013 in the BaU + 130 g + SmTr + eco scenario resulted in an additional 1 % reduction of CO_2 emissions bringing the total reduction to 31 %.

None of these scenarios deal with a penetration of electric vehicles into the system, hence the low levels of reduction relative to the Irish TIMES scenario. In the BaU + 130 g + SmTr + eco + EV scenario there is a total penetration of 82 % of electric vehicles into the system by 2050. This resulted in a total CO_2 emissions reduction of 77 % by 2050 relative to 2008.

In this final CarSTOCK scenario, the model has a steady reduction from 2.63 MJ/km in 2010 to 0.72 MJ/km in 2050. The reason for the difference in these figures is due to a longer survival rate of private cars in the CarSTOCK model relative to the Irish TIMES model; the Irish TIMES model uses a constant 15 year lifetime for vehicles while in the CarSTOCK model lifetimes are based off historic scrappage profiles which are realistically longer than the Irish TIMES assumption. This results in a larger percentage of the car fleet in the CarSTOCK model to be fuelled by fossil fuels in 2050 while the Irish TIMES model has all electric vehicles by this year. A comparison of the SEC in this scenario and the 80 % CO_2 scenario in Irish TIMES is presented in Table 1.

This final scenario was taken to be the most achievable in terms of policy measures which may be taken in Ireland in the private transport sector to reduce CO_2 emissions to match the levels of the Irish TIMES results. The overview of the results from this initial analysis is presented in Table 2 and Table 3. The percentage sharer of the stock profile by fuel type in this scenario is shown in Figure 4.

Table 2. Comparison of Emissions in Irish TIMES and CarSTOCK Scenarios.

Emissions Comparison Active Unit: gCO_2/km	2010	2015	2020	2025	2030	2035	2040	2050
TIMES 80 % CO_2 Reduction	186.93	181.71	180.22	161.20	78.07	51.92	4.09	3.49
BaU + 130 g + SmTr + eco + EV	186.14	178.13	161.61	142.27	120.01	101.77	86.25	34.96

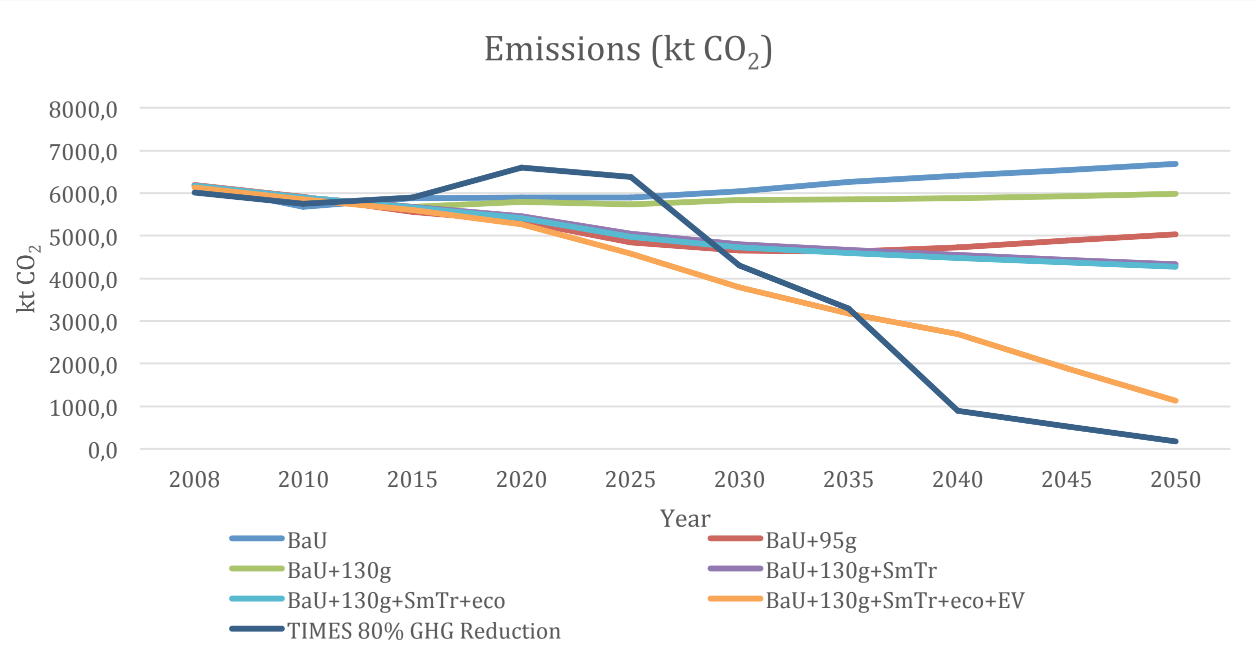

Figure 5. Emissions Reduction in CarSTOCK Scenario vs. the Irish TIMES Scenario.

Table 3. Comparison of CO_2 Emissions Reductions Percentages in all Scenarios.

Scenario	Percentage CO_2 Change in Private Cars by 2050 relative to 2008
Irish TIMES 80 % CO_2	**-97 %**
BaU	8 %
BaU + 95 g	-19 %
BaU + 130 g	-3 %
BaU + 130 g + SmTr	-30 %
BaU + 130 g + SmTr + eco	-31 %
BaU + 130 g + SmTr + eco + EV	**-82 %**

3. EVALUATING TECHNOLOGY AND POLICY FEASIBILITY (MULTI-MODEL APPROACH)

Following the feasibility analysis of the Irish TIMES model using the CarSTOCK model, it was deemed unrealistic to have a 97 % emissions reduction in the private transport sector by 2050 with 100 % EV penetration. Due to this, the Irish TIMES model was run with this same scenario but with an added constraint of total maximum EV penetration of the private car fleet of 82 % – the final value of fossil fuelled vehicle penetration in the BaU + 130 g + SmTr + eco + EV scenario in the CarSTOCK model by 2050.

This new added constraint resulted in the remaining 18 % of the car fleet consisting of diesel fuelled vehicles. The resulting CO_2 emissions reduction by 2050 relative to 2008 was 79 % which agrees reasonably well with the results of the CarSTOCK model as seen below in Figure 6. This figure also shows that the cumulative values of CO_2 emissions in both models are approximately equal over the 50 years.

Due to this relative rise in emissions in the transport sector, other areas in the energy system in Ireland are required to carry out further emissions reduction to counteract this effect. Hence the Irish TIMES model looks at the next least-cost option available for achieving this. In this revised Irish TIMES scenario the emissions are reduced further in the residential sector, services sector and in electrical generation to counteract the effects of the relative increase in the emissions in the private transport sector. The reduction in these scenarios is carried out through the increased use of electric heating and air source heat pumps in the residential sector and a higher level of wind penetration in electricity generation.

Discussion

The soft-linking methodology described in this paper could be employed for informing policy measures when there is a lack of detail in the individual sectors in a top-down least-cost optimisation model which is being used to set technology pathways for the future. In this instance, the results of the private transport fleet in the Irish TIMES model were seen to be infeasible according to the CarSTOCK model due to the lower level of detail in the Irish TIMES private transport sector. The difference in the level of detail lies mainly in the calculation of the scrappage rates of vehicles; the CarSTOCK model calculates scrappage rates based on high level historic data disaggregated by engine size and fuel type while the Irish TIMES model uses a 15 year life per vehicle. This is the reason behind the ease of mitigation towards petrol and diesel fuelled vehicles in the Irish TIMES model while the BaU + 130 g + SmTr + eco + EV scenario in the CarSTOCK model has 18 % of vehicles in the private transport fleet fuelled by petrol and diesel in 2050 in the most ambitious scenario, regardless of the stoppage of sales of fossil fuel vehicles from 2030 onwards. The higher level of detail in the CarSTOCK model allows for the evaluation of particular

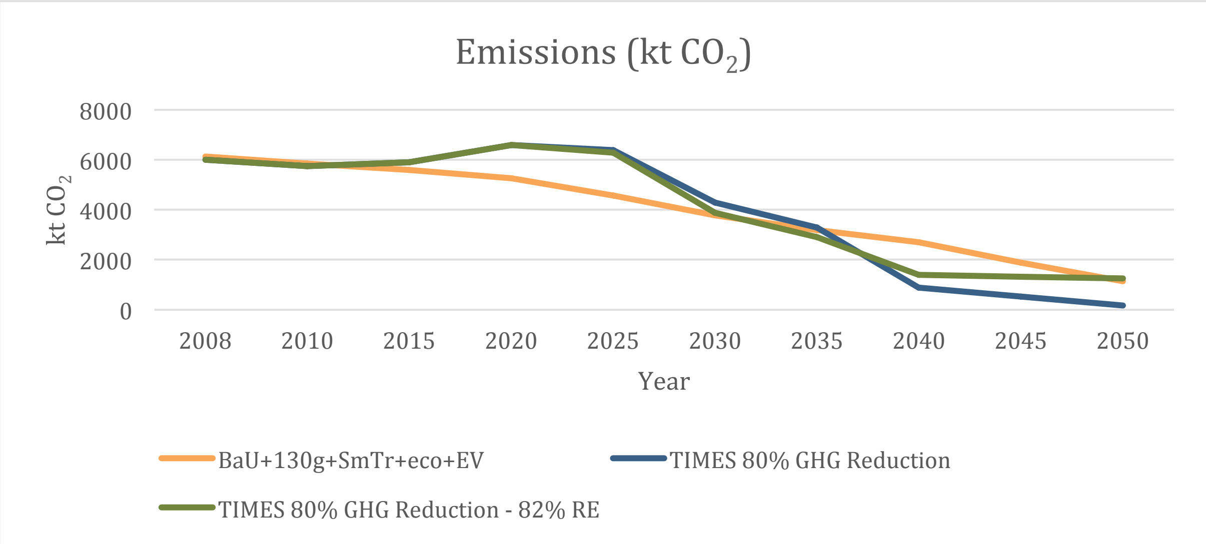

Figure 6. Irish TIMES Emissions Reduction with 82 % Electric Vehicle Constraint.

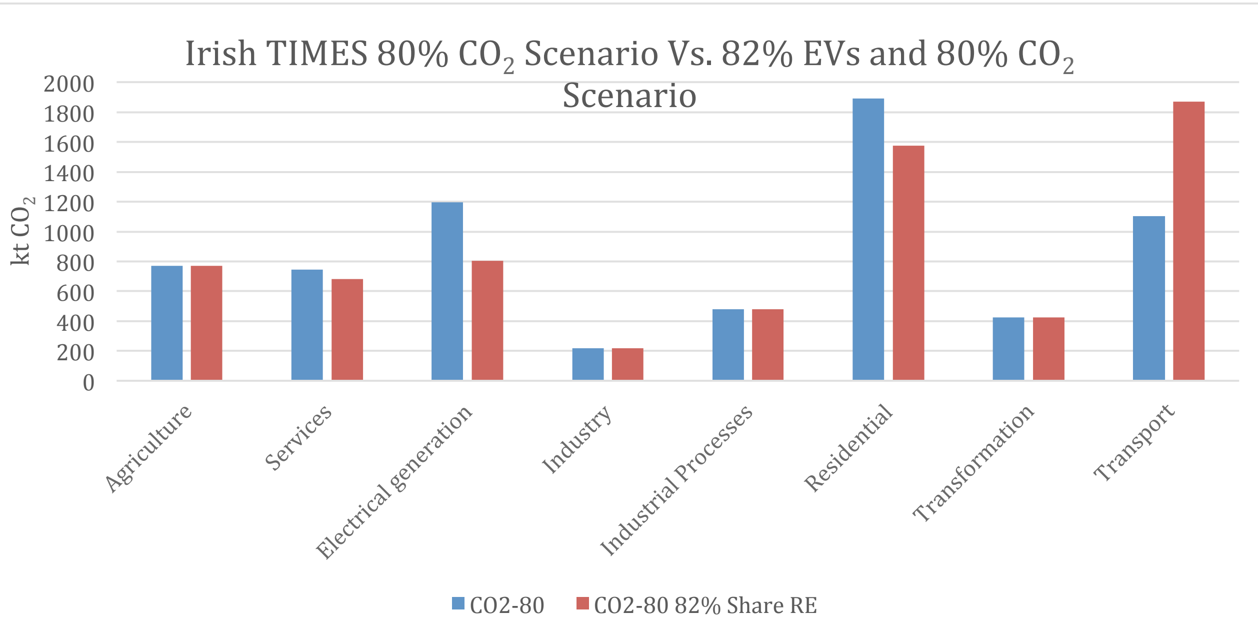

Figure 7. Comparison of Irish TIMES Scenarios.

aspects of the implementation of policies such as varying penetration rates of renewable vehicles and the interaction effect.

The Irish TIMES model is capable of determining the least-cost technology pathway to be taken for a given constraint, however it is not be sufficient for informing which policy measures may be taken in reaching these results. By combining this top-down modelling approach with the bottom-up modelling used in the CarSTOCK model, a greater insight into which policies may be effective is acquired. This also allows for the level of ambition required from these policies to be checked against the overall top-down targets. This methodology may be applied to any country which have top-down and bottom-up policy evaluation models readily available; linking the two models may allow for an increased level of accuracy of the overall results of the energy system in a country.

It is important to be aware that all energy models have inherent assumptions and limitations and that the two models employed here are no exception. A significant assumption underpinning the Irish TIMES model are the projections for economic growth, which are derived from the outputs of a separate model, and which for the Irish TIMES model remain as exogenous. A current limitation of this approach is the absence of feedback between the output of the Irish TIMES model, i.e. the energy system and the input level of economic growth. Another limitation of the Irish TIMES model is the model's inability to account for behavioural aspects and so the modelling of consumer behaviour is generally limited to simple price response, i.e. non-price related behaviour is not represented. For the CarSTOCK model, there is a similar limitation in terms of behavioural modelling, which currently prevents exploration of the impact of the rebound effect. The focus remains on technological parameters and the rebound effect is not accounted for in either model.

This soft-linking methodology can be applied to all sectors dealt with in a least-cost optimisation model. Work has been carried out previously dealing with soft-linking the Irish TIMES model with a residential sectoral model (Deane J. , et al., 2013) where the Irish TIMES model was linked with the Irish PLEXOS model, an integrated power systems model of Ireland, and the ArDEM model, a sectoral simulation model of the residential heating demand in Ireland. Ideally creating a soft-link between an optimisation model and sectoral simulation models of all sectors dealt with, the accuracy of the results will increase allowing for effective informing of policy measures in a country.

Conclusions

A least-cost energy systems optimisation model can provide useful insights into the technology pathways which may be taken to achieve certain policy goals, however they do not inform policy measures which lead to these results and a lack of detail in any sector may lead to unfeasible results. Bottom-up sectoral simulation models may provide a high level of detail for one particular sector and can also simulate certain policy roadmaps, however it does not allow for constraints to be imposed in the same manner as least-cost optimisation modelling. The challenges encountered by these two individual modelling methods can be overcome by creating a soft-linking methodology between the top-down and bottom-up models. This allows for a more accurate insight into the policies measures which may need to be taken to effectively achieve a CO_2 emissions reduction goal.

By carrying out this combination of top-down and bottom-up energy efficiency modelling, a more achievable policy pathway is determined. In this case, the top-down method used by the Irish TIMES model was producing results which were deemed difficult to achieve for the private car sector according to the CarSTOCK model. By combining these two models together, this difficulty was identified and a more realistic pathway was calculated.

Further research in this area would involve creating an automatic link between a sectoral simulation model and least-cost optimisation model. This would carry out an iterative method between the two models: the optimisation model would take a constraint, provide results, and then check the results against the sectoral simulation model. If there was a disagreement between the models, a new constraint would be entered into the least-cost optimisation model and then re-run. This method would continue until an agreement was found between the two models.

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